The Institute of Fuel
(South Coast Section)

POTENTIAL FOR POWER

A Symposium on the Prospects for Power from Currently Unconventional Energy Sources

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THE POTENTIAL OF WAVE POWER

by

I. Glendenning

SUMMARY

The wave energy arriving on the west coast of the United Kingdom represents a very substantial energy resource, amounting on average to more than twice the present installed capacity of the CEGB. Recent, comprehensive, studies by the CEGB (1) (2) and the National Engineering Laboratory (3) suggest that although there is no obvious technical reason for being unable ultimately to harness much of this energy, and many methods have been proposed, there are still considerable uncertainties over the choice of wave power system and its economics. Wave power does show sufficient promise however to have been made the subject of serious studies supported by the CEGB and the Department of Energy (4).

In this Paper the potential of wave power and some of the more promising methods of harnessing it are discussed, together with an appreciation of some of the many technical and engineering problems which still need to be examined, and a discussion of the impact of wave power on the environment. By considering the results of recent research and their impact on wave power economics it is argued that wave power could be exploited to conserve fossil fuels but is unlikely to be competitive with nuclear power.

THE POTENTIAL OF WAVE POWER

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I. Glendenning

1. INTRODUCTION

When, about two years ago, the Research Division of the Central Electricity Generating Board examined the renewable energy sources as part of a comprehensive long-term study wave power seemed to be a particularly attractive prospect because the scale of the resource was appropriate to the needs of the United Kingdom and, although the precise method was by no means clear, it was evident that this energy could be harnessed by a multiplicity of small units. This essentially modular characteristic meant that development, and even installation programmes at full scale, could be contemplated without the massive single investments required by some other options.

A small research programme was therefore established at the Board's Marchwood Engineering Laboratories to study the characteristics of this resource in more detail, to identify methods of harnessing it, converting it to a useful form and transmitting it to shore. Despite the many technical problems which came to light, our early findings were encouraging and were reported to the Department of Energy's Advisory Council on Research and Development, ACORD, and, together with the National Engineering Laboratory study (3) commissioned by the Department of Energy, were instrumental in establishing the National Programme (4). The Board is supporting this programme, both through membership of the steering committee and its own independent studies.

The next 1½ to 2 years will be devoted to assessing the technical feasibility of exploiting wave energy, determining the contribution which it could make towards meeting the UK's long-term energy requirements, in particular as a source of electrical power, and to making first order assessments of the cost of implementing a wave power programme and the possible economic benefits which might arise.

In this Paper we will examine the progress which has already been made and highlight some of the key issues which still have to be resolved. Finally, although it is far too early to make any meaningful estimate of the ultimate economics of wave power, we will outline some of the factors which must be included in assessing the economic case.

2. A MAJOR RESOURCE

The first and obvious requirement of an assessment of wave power is an understanding of the energy source, both its scale and its overall characteristics, since these determine both the potential and the pitfalls.

Some Background

Textbook linear wave theory (16, for example) is an excellent basis for understanding the basic characteristics of wave power. A simple progressive sinusoidal wave of amplitude a, wave length λ, and

period T, travelling in deep water (by which it is meant that the depth is greater than half a wavelength) has a surface profile

$$y = a \sin(kx - \omega t)$$

in which $k(= 2\pi/\lambda)$ is the wavenumber and $\omega(= 2\pi/T)$ is the angular frequency.

Fluid particles in the surface move in circular orbits of amplitude, a, with velocity amplitudes of $a\omega$, and fluid particles below the surface also move in circular orbits of decreasing amplitude, as $a\exp(-ky)$, where y is the depth. The total energy, E, per unit of surface area contained in the circular fluid motions (kinetic) and in the variation in potential energy above and below the mean water level is

$$E = \tfrac{1}{2}\rho g a^2 \qquad (1)$$

where ρ is the density of sea water and g the acceleration due to gravity.

The speed with which the wave propagates, the phase velocity c, can be written variously as

$$c = \lambda/T = \sqrt{(g/k)} = gT/2\pi \ , \qquad (2)$$

(the longer the wavelength and period, the faster it travels), and the speed with which the energy propagates, the group velocity v, is one half of this.

The power associated with a monochromatic wave is therefore

$$P = Ev = \rho g^2 a^2 T/8\pi \qquad (3)$$

per unit width of wave front.

It will also be seen from the forms of equation (2) that the wavelength and period are simply related as $\lambda = gT^2/2\pi$, a 7 s wave having a wavelength of 75 m, a 10 s wave one of 150 m and so on.

Waves in the Ocean

Ocean waves are, of course, generated by the wind so wave power is in fact another form of wind, and therefore solar, power but with an important difference. Water waves propagate energy at an extremely high efficiency so the ocean is analogous to an exceedingly large windmill and even when waves are not being generated by a local wind (the wind sea), there is a good chance of waves from remote wind fields (the swell sea) being present.

The Institute of Oceanographic Sciences and other organisations, collect data from wave buoys, weather ships, light ships and sightings from ships in passage. A particularly comprehensive set of published data for the North Atlantic comes from the weather ship site 'India' (50°N 19°W), (Draper and Squire, 1967). In line with usual practice these data are presented (18) in terms of a 'significant wave height', H_s, and a 'zero crossing period', T_z. The location of 'India' is shown on the map, Figure 1, and the wave conditions measured there are believed to be representative of those existing to at least the continental shelf and probably much closer in shore. The frequency of occurrence of H_s, T_z combinations is shown on the scatter diagram, Figure 2, from which it is clear that the most frequent wave states are in the 1 to 5 m high, 7 to 11 s period region.

In interpreting these data it is important to recognise that measurements of H_s and T_z cannot simply be equivalenced to a monochromatic wave and the power estimated using equation (3). Although swell components can be substantially plane and monochromatic when the generating site is a great distance from the measuring point (19), the local wind sea is far more complicated. Usually it is treated as the linear sum of many monochromatic waves of random relative phase distributed both in direction, θ, and across the frequency spectrum, f. The principle direction, θ_0 is usually the wind direction and the total spectrum is represented as the product of a one dimensional spectral density function $\varepsilon(f)$ and a spreading term $g(\theta-\theta_0)$ by which means g need not be considered when estimating wave power levels but will be important when considering the efficiency of the devices.

The preferred form of $\varepsilon(f)$ is that of Pierson and Moskowitz (20)

$$\varepsilon(f) = Af^{-5} \exp(-Bf^{-4})$$

where A and B are constants related to the wind speed and fetch or other wave parameters. For wave power studies it is convenient to employ the definition in terms of H_s and T_z in which

$$A = H_s^{\,2}/4\pi T_z^{\,4} \text{ and } B = 1/\pi T_z^{\,4}$$

and examples of $\varepsilon(f)$ for typical 'India' sea states are shown in Figure 3. It will be seen that the energy of the wave system is concentrated at the low frequency end of the spectrum in waves longer than represented by T_z.

From the analysis of Count and Robinson (8) it can be shown that, when H_s is measured in metres and T_z in seconds, the power of a wind generated wave system represented by this particular distribution is

$$P \sim 0.55\, H_s^{\,2} T_z \text{ kW m}^{-1} \text{ of wave front normal to } \theta_0.$$

This estimate assumes a degree of filtering in the data collection system and is accurate to about 30%, perfectly adequate for our present needs.

The data in Figure 2 will now be seen to represent power levels ranging from 0 to 2 MW m^{-1} with an average of some 80 kW m^{-1} and a most frequent power level of about 50 kW m^{-1}, in line with the power base employed by previous authors (1), (2), (3), (5) and (9).

Taken along 1500 km or so of the UK west coast these data imply an average wave power of 120 GW or more than double the installed capacity of the CEGB and 5 times the annual average demand, and even taking slightly lower average power estimates for inshore locations of 70 kW m^{-1} off Scotland and Ireland and 20 to 50 kW m^{-1} off SW England (3) wave power is clearly a very large resource.

3. VARIABILITY IN THE SUPPLY

Just as the sun and the wind cannot be relied upon for a continuous supply of energy, so wave power is also an extremely variable resource.

A closer examination of the 'India' data shows not only that for about 1% of the year waves higher than 10 m and periods greater than 11 s are experienced, with average powers of > 1 MW m^{-1}, but for a further 1% of the year there is very little wave power at all. These storms and calms occur at random which means that wave power cannot be regarded as "firm power" and its value will have to be assessed for its ability to conserve other forms of prime energy and reduce running costs on conventional plant and not as an alternative to nuclear or conventional fossil fuelled power stations.

It is reasonable to expect that there will be higher powers and fewer calms in winter than summer. The CEGB (2) has produced seasonal load factors from the 'India' data, Figure 4, which highlights the seasonal variation in the energy supply, more in winter than in the summer, which compares favourably with the pattern of electricity demand in the UK. This is widely regarded as an attractive feature of wave power particularly when the high winter load factors at useful power densities are taken into account.

Despite the limited statistical nature of the 'India' data, about 1 year of data accumulated over 10 years, the CEGB (2) have also drawn attention to the fact that power levels vary enormously from year to year. In addition, Figure 5, they show that even in a winter month periods of very low power availability can extend to several days emphasising the non-firm characteristic and providing strong evidence that to incorporate storage to give a continuous output would require uneconomically large capacities.

On much shorter timescales, Figure 5 also shows that changes in the incident power can be very rapid - 200 kW m^{-1} in only a 3 hour period being quite common. This extreme variability extends even to the minute by minute time scale where the random nature of the wave generation process is such that in a 'stationary' sea, i.e. one whose spectrum is not changing with time, instantaneous powers of more than ten times the mean will occur. In these situations however storage would be of great value and is likely to be economically feasible.

Finally we should consider the directional characteristics of the energy supply. Hogben and Lumb (21) have presented data on mean direction to indicate that at 'India' only 45% of seas approach from the west, while 24%, 19% and 12% approach from the south, north and east respectively. It follows that not all the energy available at 'India' will be present at more sheltered inshore sites. Furthermore since the energy is spread about the mean direction, usually represented as a $\cos^{2s}[(\theta-\theta_0)/2]$ function in which s can range from 1 at high frequencies to 10 or more at low frequencies, it is clear that the power drawn from a given sea will depend on the directional characteristics of the device.

4. THE WAVE POWER PROBLEM

Before proceeding to a more detailed discussion of wave power systems, it is worth considering what characteristics an ideal system should have in the light of the known characteristics of the energy supply.

It is apparent that on average the availability of wave power is sufficiently large that it is a potentially valuable resource. A satisfactory return on capital will most probably require the operation of converter plant at a fairly high load factor, particularly in the winter when the opportunities for saving expensive fossil fuels are greatest, and on the basis of Figure 4 this would imply designing for 50 to 150 kW m^{-1}, noting that the system will be required to continue to produce power at its design level even when the incident wave power exceeds this level.

The ideal wave power system will therefore be one which can accept a random energy input of extreme variability, be able to cope with a wide range of incident wave directions and incorporate sufficient short term storage to smooth minute by minute or even hour by hour fluctuations in the energy supply. Whilst it will be very efficient in low and moderate seas it will be very helpful if the overall characteristics of the device and its associated conversion and transmission system make it progressively less efficient as the incident power increases to extreme levels. By this means a more even output and better use of generation and transmission capacity would be achieved.

The problem then is to identify a system with these general characteristics which can be built to survive the hostile extremes of the ocean environment with good reliability and long life at a cost which can be justified in terms of the capitalised value of the fuel savings it would make possible.

5. WAVE POWER DEVICES - GENERAL

Up to the present time most of those who have interested themselves in wave power have concentrated their efforts on the device which is put to sea to couple to the incident wave system. As a result many patents exist for ramps, floats, flaps, systems involving fixed and moving air bells and 'wavepumps' of various descriptions. A very comprehensive survey of the patent literature can be found in (3). With certain notable exceptions most of these ideas presume a passive device coupling to either the 'potential' or 'kinetic' energy components, i.e. the surface displacement or the circular fluid particle motions. The principle types are:

Ramps

Strictly speaking only ramp and similar schemes can be regarded as passive. The forward momentum of the fluid in a wave travelling into shallowing water is converted into an hydraulic head on a sloping sea wall, water being carried over the top to charge a 'high' level reservoir. Power can be produced by returning water from the reservoir to the sea through a low head turbine working on the difference between the reservoir and the mean water levels. The only moving parts are the turbines and the only variables are the slope and height of the ramp. Such a scheme was proposed for Mauritius (22), taking advantage of the small tidal range and a particular coastal structure, but for the British Isles, where the tidal range is large compared with likely ramp heights, ramp schemes do not seem to be attractive despite their undoubted simplicity, reliability and substantial inbuilt storage capacity.

Floats

The visible part of a wave system is of course the surface motion and not surprisingly there have been many schemes for allowing floats to heave in response to this motion taking power out at a pump or similar device attached to a mooring line. The problems with such schemes are that either the link to the sea bed is very complicated and expensive or the float does not restrict itself to the heave motion from which energy is to be extracted but it pitches and surges with an attendant loss of performance. One interesting exception is the so called resonant point absorber (13) which can, in principle, extract energy at a high efficiency from a wave front of width equivalent to $(\lambda/2\pi)$ regardless of its own size. Evans (12) has confirmed this result theoretically but notes that for small devices, very large amplitudes of motion are required.

Flaps

In deep water, the horizontal component of the motion of the fluid, which decays as $\exp(-ky)$ with increasing depth, can be closely matched to an oscillating vertical flap hinged at something like $.4\lambda$ below the surface. In between the completely undamped motion, when the flap moves freely with the incident wave and generates a new wave with the same energy to the rear, and the overdamped condition, where the flap barely moves and the incident wave is reflected, there is an optimum damping when almost half the energy can be extracted, the remainder being contained in reflected and transmitted waves of reduced size. Systems of this type also require complicated and expensive sea bed connections.

Air Bells and Wave Pumps

Early ideas for these devices were also based on the motion of the fluid surface. It was conceived that if an air bell was supported with its open bottom a little way below the water surface, passing waves would cause a cyclic pressure variation in the trapped air and, therefore, if the vessel were connected through a rectifying valve arrangement to a small turbine, power could be produced. This is the operating principle of the 300 or so self-powered navigation buoys, designed by Masuda in Japan. They are in use around the world but their conversion efficiency tends to be very low, although this is of no concern in this particular application.

Wave pumps also work off subsurface pressure variations by pumping fluid around a circuit containing a hydraulic motor using a succession of suitably spaced collapsible cylinders connected through non return valves. A common error made in designing such systems is to assume that the pressure at all depths is the hydrostatic head $\rho g(y + \xi)$ where y is the depth and ξ the instantaneous wave elevation. In fact the pressure amplitude decays at the same rate as the velocity amplitude and neither system will function if deeply immersed.

6. PROMISING DEVICE CONCEPTS

Although the general device types described above seem to be unpromising, it is in fact variations on these early themes which are among the leading contenders for highly efficient and hopefully practical devices and which are now being developed in the DoEnergy/CEGB studies.

The Cockerell pontoons (6), Figure 6, can be regarded as a series of floats which progressively extract the energy of a wave as it progresses down the line. The ingeneous aspect of this invention is that by hinging the floats together and extracting power from the relative motion of adjacent elements, the need for complex sea bed couplings is minimised to the mooring, power and control system connections.

The Salter duck (5,10) similarly overcomes the basic limitations of the flapping plate by virtue of its cleverly designed shape (Figure 7). This was chosen such that when the duck oscillates in roll about the correct centre, the front of the duck, which faces the waves, moves almost exactly with the fluid motions absorbing all the energy. The rear section, which is circular, does not displace any fluid and cannot therefore generate a transmitted wave. In two-dimensional tank tests using plane monochromatic waves, Salter had demonstrated a 90% efficiency by late 1974. (5,11).

Working on the principle (as Cockerell) of progressively extracting energy from a number of relatively inefficient units, Masuda has proposed and tested a number of configurations of multi-chamber air buoys. In the present DoE programme however the National Engineering Laboratory are developing the idea further to a much more sophisticated single chamber device, Figure 8.

Experimental Progress

Experimental studies of these devices have already shown that each is capable of development to a high efficiency compact wave power converter with the required overall characteristics. Their widely differing appearances present different engineering problems and it is hoped that one of them could ultimately be developed as part of a practical system.

Salter, in particular, has explored the dynamics of his device in great detail and whereas early work (11) had suggested that ducks would need to be 30 to 50 m diameter to couple adequately to North Atlantic waves his more recent experiments suggest that a dramatic reduction in the required size is possible, with an enhanced overall performance. In these experiments he has shown that by carefully controlling the distribution of his structural material he can, with a simple power take-off characteristic produce a peak efficiency of 85% and exceed 50% over a full 2:1 frequency band, and by applying more sophisticated control can exceed 80% efficiency over an even larger band. What makes these results even more remarkable is that if this can be achieved at full scale, devices for the North Atlantic need be no more than 10 to 15 m in diameter. These results are discussed fully by Salter in (10) and are reproduced in Figure 9.

Recent tank tests carried out by the CEGB on the Cockerell raft system indicate that it is possible to achieve broadly similar performance characteristics with that device. Though the pontoon system has a greater overall length, its shallow draught may mean that when sized for the North Atlantic it will require no more structural material than the duck. The results which are currently available from NEL suggest that their device also displays the same overall characteristics and has the advantage over the others of having no large moving parts.

Sea Performance

A plot of 'efficiency' versus 'frequency' measured for monochromatic waves in tanks does not give a real picture of how the devices will operate at sea and how their performances match to the requirements set out in section 4. To indicate what we may hope to achieve, the results from Figure 9 are reproduced as 'sea performances' in Figure 10 in which the spectral distribution of wave energy in the sea has been taken into account. The size of the device has been chosen to maximise the

efficiency in low and medium powered seas (small T_Z) and to be less efficient in high powered seas (large T_Z). Three examples of the Salter duck are included to show the sensitivity to device size. Also included on Figure 10 are sea efficiencies for the other preferred devices based on experimental results to date. These are shown merely to emphasise the similarity of response which can be achieved and not to indicate their relative capabilities.

One characteristic which is not taken into account by these performance considerations is the ability of the device to accept energy from a number of directions. If, ultimately, one recognises that a very long line of devices will be required to produce significant quantities of power, 1000 MW or more, a side-to-side absorption capability is not required although the NEL design could be made to be genuinely omni-directional and could function in this way. The NEL buoy could therefore be made to absorb energy from the rear as well as the front and, if so designed, so too could the contouring raft. Only the Salter duck, being deliberately asymmetric, would not obviously be able to extract energy from the rear. All of these devices can be expected to cope with a fairly wide range of incident directions, and directional spreads, of the wave energy so long as the width of each element is kept well below a wavelength and this has been demonstrated both on wave power devices and ship models.

Finally, all the experiments have been carried out in tanks and, except for the CEGB pontoon tests, have been of models operating from a fixed datum. The full effect of operating devices as moored free floating systems with realistic, often non linear, power off take equipment has therefore yet to be determined, and each of these factors is likely to reduce the performance of a given device.

Theoretical Progress

Within the CEGB a comprehensive theoretical model of the hydrodynamics and dynamic response of devices of the duck and pontoon type has been developed (24) from work by Ursell (25, 26), Evans (12), Katory (27), Newman (28) and Takagi (29). The predictions from the theory, which correlate well with the experimental evidence available, show that great care must be taken in interpreting model results to full scale. For example, Salter's duck would, as he suggests, have to be made in self-stable units consisting of several ducks mounted off a single spine if his results are to be reproduced at sea. The theoretical model shows that an isolated duck, set up as suggested by Salter's fixed centre work, would perform relatively badly because of the heave and sway motions of the spine, although changes in shape, size, ballast distribution and loading characteristics could also be effective in counteracting the performance loss due to unwanted motions.

Although still at an early stage of development, such theoretical work is already making an impact on device design and system studies and in due course will be essential to the overall optimisation of complete wave energy conversion systems.

7. OVERALL SYSTEM CONSIDERATIONS

It must be recognised that the device for extracting the wave energy, although vital, is only the first link in a long chain of equipment needed to convert the wave energy into a usable form, transmit it to shore and feed it into either the electricity supply system or, possibly, that of some other energy consumer or distributor. If a single key area can be identified in the study of wave power it is probably the design and engineering of an economic and efficient conversion and transmission system connecting the device to the consumer. It is already clear that this system will have to accept a random and extremely wide ranging energy input but it is only now that the wave and device characteristics are better understood that a meaningful study of the options can be contemplated.

Conversion and Transmission Systems

A simplified block diagram showing the probable component combinations which will make up a complete wave power system is shown in Figure 11. Many detailed, but purely speculative, conversion systems can be conceived within the framework of this diagram but here only some of the more obvious routes and problems will be described.

Wave/Mechanical to Electricity

The first major problem arises at the mechanical connection between the device and its load, whether the latter is electrical or hydraulic. The initial motions are the slow oscillation (at typically .1 Hz) of one part of the device relative to another. Except in the case of the Masuda system in which displaced air and air turbines are an integral part of the design, a mechanical linkage will be required between the moving structure and the load. Possible linkages include levers or gears, which could be incorporated into bearings, or even chains, but the very low initial velocities mean that very large torques are involved in transmitting powers which are modest by power engineering standards. For example, if a device produces 1 MW whilst oscillating with an amplitude of 15^{o} at 0.1 Hz, the torque ampltiude at the device is about 1200 tonne m which is nearly eight times the torque on the shaft of a 500 MW power station alternator.

In general, it is difficult to contemplate mechanical rectification of the device output and so not only is the first mechanical connection subject to the full randomness of the wave energy supply, it will also in general be subjected to reversing loads at the wave frequency.

Once having obtained mechanical motions at a convenient speed there is next the problem of energy conversion to a more usable form. Glendenning and Count (2) briefly discuss the advantages and disadvantages of 'direct electrical' and hydraulic/electric loading and it is most probable that the greater ease of handling low speeds and large forces, together with the convenience with which short term storage can be included, will favour the latter approach. Either way many other factors need to be considered including the choice of the optimum plant/machine rating (cost and performance), the problems of combining and controlling the outputs from many random sources (the adjacent devices) and the delivery of energy to, say, the CEGB grid in a form which does not create serious operational difficulties on the main system.

It is perhaps worth emphasising here that in practice there is bound to be a mismatch between the recommendations of the system designer and the requirements of the device designer. The effect which the inevitable compromise will have on the performance could be quite marked and will have to be determined before economic arguments can be settled with any degree of confidence.

The Floating Factory

The one approach which could avoid many of these problems is the so called 'floating factory' concept first introduced by Denton, et al. (1). There have been many suggestions of this type ranging from 'off shore aluminium production', where it is presumed that electricity is produced and used at sea so saving on transmission costs, to hydrogen production, which again presumes electricity produced at the device but from which the ultimate product could be either the electrolytically produced hydrogen itself or a synthetic liquid fuel. One very interesting floating factory option is the concentration of heavy metals from sea water which 'only' requires that the device pumps large volumes of sea water through separation beds. This could, amongst other things, provide the UK with its own source of uranium fuel for an extensive reactor programme. All of these alternatives are being considered in the UK programme.

8. THE PERFORMANCE AND APPEARANCE OF AN INTEGRATED SYSTEM

It will by now be clear that whilst wave power shows promise, there is still a very long way to go before it will be capable of commercial exploitation but there is a sufficient understanding of the various aspects of the wave power problem to begin to build up a picture of a developed system and its performance.

The extreme variations in power deduced from Figures 2 and 5 are, first of all, modified by the characteristics of the sea performance, Figure 10. Although it may well be possible to realise the very high efficiencies quoted by Salter, for the moment we will for illustration use the more modest fully floating pontoon results. Under 'normal' operating conditions in a moderate 3 m high sea with a 9 s period, of about 45 kW m^{-1}, the device would produce about 28 kW m^{-1}. A 14 m, 14 s sea of 1.5 MW m^{-1} will produce very substantially more output but the reduced efficiency limits this to about 420 kW m^{-1}.

To design the conversion and transmission system to transfer 420 kW m^{-1} efficiently would, however, demand that at least the first stages of the conversion to be rated at 4 MW m^{-1} or more because of the randomness of the energy supply. This in turn would mean that this plant was badly under-utilised because of the very low output load factor at this power level. Rating at less than this output, on the other hand, would progressively cause a loss of power from the peaks. For a linearly loaded device, with a constant damping factor, K Nm s^{-1}, the device velocity, v, will be Gaussian distributed and, since the power output is

$$\frac{1}{T}\int_0^T Kv^2 dt,$$

the mean power output can be determined as a function of the peak power rating. This is shown as an additional "overload efficiency" related to the ratio (peak power/input rms power) in Figure 12, for cases when either the system continues to produce power at its peak rating when overloaded or when under overload conditions output is lost. By choosing a reasonable peak rating of, say, 150 kW m^{-1}, we now find that the 'moderate' sea hardly overloads the system and the full 28 kW m^{-1} is produced, but at 420 kW m^{-1} the system is so overloaded that output is cut to about 100 kW m^{-1}. In fact applying these devices and overload efficiencies to the 'India' data shows that with a peak rating of 150 kW m^{-1} and a continuous rating of about 90 kW m^{-1} (which is all the transmission system need cope with) an annual average output of 27 to 34 kW m^{-1} could be achieved depending on the spectral distribution assumed for the long period low height seas, Pierson-Moskowitz or swell respectively. Both the overall efficiency and the annual load factor are in the range 0.3 to 0.38, and in winter the load factor will be very much higher though the efficiency is less. The choice of device size and plant rating are in fact particularly important factors in the optimisation of wave power economics and is currently the subject of a detailed study in the CEGB.

The most probable plant layout for the example given above, which is fairly typical, can now be postulated. It can be seen that by rating the system at about 90 kW m^{-1}, a 1000 MW installation, with a single transmission connection to shore, need only be about 11 km long. It would be made up of many individual ducks, pontoons, or buoys, each no more than 30 to 50 m wide so as to give the desired directional characteristics, moored singly or joined in stable sub-assemblies along a line 10 to 20 km from shore. Each device group even if loaded hydraulically will probably be connected electrically through low power flexible cables to a centrally placed control centre-cum-transmission head. At this sea going substation, rather like a large oil platform production, the device outputs would be combined and smoothed and fed into a main HV transmission line to shore where the power would either be used directly or connected to the grid.

9. LIVING WITH THE ENVIRONMENT

Two environmental impacts are important, that of the device on the environment and that of the environment on the device.

Impact on the Environment

One of the major attractions commonly claimed for all of the renewable sources of energy is that they are non polluting. Except for possible spillages of oil from hydraulic or lubrication circuits this certainly applies to wave power. There are other environmental impacts which will have to be taken into account and a brief study carried out within the CEGB identified some of these and provided a qualitative assessment of their importance.

The visual impact of the device is only likely to be significant if it must be located close in shore. All the more promising devices are intended for deep water operation, more than 10 km from the coast, and have such a low profile that they will not be visible from land. The main visual impact will be due to the inshore terminal of the transmission link. Unless say hydrogen is the selected transmission medium and a chemical plant or some other industrial complex is established to process or use the hydrogen directly it is landed, this termination need have no greater impact than existing large substations.

The construction and operation of wave power systems will create a need for large industrial complexes, dwellings and, possibly, new harbour facilities to be established and serviced by road and rail. Where no alternative exists but to develop green field sites then this would give rise to strong objections.

The main area where wave power might be expected to impact on the environment is in its modification to the sea. An efficient wave power device is after all an ideal breakwater which could produce effects such as altering the sea bed by, for example, creating sand bars close to the device, reducing littoral drift and modifying coastal erosion and deposition patterns. The likely extent of these effects is not known but since the devices will tend not to extract much energy from storm waves, and short choppy seas are likely to be regenerated in the 10 to 20 km between the device and the shore, there would seem to be a very good prospect that these effects would not be particularly significant.

Similarly, ecological effects are not likely to give cause for concern and it may even be that the presence of large structures could attract new species of fish and plant life or encourage larger colonies of existing species. In fact, it is likely that the reverse effect of marine fouling on the performance and maintenance of devices will be much more severe.

The two areas where serious objection could be raised and which will therefore have to be studied very carefully, are the obstruction to navigation and the consequences of collisions with ships and damage to coastal installations including harbours and even fixed platforms which could result from a device breaking free of its moorings.

Impact of the Environment

Storms

One aspect of wave power common to all devices relates to the ability of each to cope with the very severe conditions which exist in the Atlantic. The scatter diagram indicates a .1% occurrence of waves with a significant wave height of around 14 m corresponding to peak waves of around 20 m in height and the predicted 50 year wave is 34 m high.

The air-water interface is the worst place to be in severe storm conditions and this has led to thoughts of arranging for devices to submerge to a safe depth in extreme conditions. However, the high cost of submarine technology would suggest that if possible the devices should be designed to ride out storms. Examination of the scatter diagram, Figure 2, shows that on only relatively few occasions does the apparent wave slope (H/λ) exceed 1:20. Although slopes of 1:10 will in fact be common in individual waves it is nevertheless clear that in general the extremely high seas will have a proportionately long wavelength and period and devices could well be expected to ride such waves. The reductions in the performance of devices at large wave periods measured in model tests tend to confirm this. Against this, very confused crossed seas can occur which could lead to erratic and damaging structural motions and there must in addition be a probability that very steep waves and plunging breaking waves will occur. No statistics for the occurrence of plunging breakers have been found, but if they should occur the effect on devices could be catastrophic and this topic requires very careful study. Similar questions arise when considering the extreme loads which mooring systems will be required to withstand.

Reliability, Maintenance and Plant Life

In a situation where it is not at all clear what components are likely to be included in the selected 'best' system it is only possible to indicate the range of issues involved. It has been suggested that wave power devices should be designed and constructed as cheap expendable units which can easily be replaced or salvaged. At present it is not at all clear that it will be possible to consider units either to be 'cheap' or in any land based sense 'easily replaceable' except as complete installed units. On both counts therefore there would seem to be a strong incentive to design the device and machinery as a maintainable unit of the highest reliability and life.

The main structural elements, which, because they are not required to carry cargo, can have a much higher proportion of their displacement weight in structural material than is common in shipbuilding practice, should be capable of achieving a very long life. Surviving Mulberry Harbour units point to the potential longevity of sea going reinforced concrete structures which must, on cost grounds alone, be strongly preferred to steel.

Exposed hinges, bearings or even gears, particularly those which are below the water line on the other hand, cannot be expected to have a long life unless units which can be guaranteed 'sealed for life' can be produced, no doubt a very expensive option. Otherwise the system must be designed so that the consequences of the failure of exposed components do not put either the main structure or the take off machinery at risk or alternatively that their replacement should be 'relatively' easy.

As for the conversion machinery itself, whilst it is again possible to contemplate sealed units exposed to the elements, inboard mounting in as close an approximation to an engine room environment as possible would be much better and may be essential for an acceptable life. In this way it should be possible to provide access to the plant and machinery for routine servicing and maintenance, during calm periods at least, which has an impact on the structural design.

There are many other issues to be considered under this heading including the effect on the security of the whole system, of the failure of one part either through storm damage or even collision, the need for workshops on board devices or the provision of support ships and the necessary harbourage and so on.

10. PROSPECTS

It has been demonstrated that ocean waves are an abundant source of power, possibly the largest exploitable naturally recurring source available to the United Kingdom. Several potentially efficient device types have been identified which need to be no larger than is commonplace in shipbuilding. Having taken account of the likely characteristics of these devices and their associated power conversion equipment, it has been shown that the extreme variability of the energy source can be reduced to more manageable proportions. Output power densities, on the other hand, remain at a sufficiently high level that 'power station sized' assemblies of about 1000 MW may need to be no more than 10 to 20 km long. Although wave power cannot be regarded as firm power there is a seasonal variation in the supply which corresponds to the variation in demand on the CEGB system. There is, in addition, the possibility that the scale of the weather, and therefore wave, system is sufficiently small in relation to the United Kingdom, that the combined output from

widely spaced installations could be more consistent than the output from each independently.

There have been many claims, extreme and moderate, for and against the development of wave power based on assessments of the potential economics. In the situation where so many technical and engineering questions are unresolved this is hardly surprising. The recent studies (1), (3), (31) have, however, all fallen in the same £400 to 800/kW cost band although Glendenning and Count (2) argue that a £/kW value is not particularly meaningful in assessing the value of an energy saving system.

Recent studies at Marchwood, using the analysis outlined in section 8 to determine plant ratings and the total energy output, suggest that so long as transmission and generator components do not require expensive development and so long as the infrastructure required to construct, deploy and maintain a wave power system does not become too significant (and it might) costs and values could be of the same order. This would seem to confirm wave power as a leading contender among the naturally recurring energy resource options.

Taken overall, it would appear that if satisfactory solutions can be found to the many formidable technical and engineering problems without incurring an undue increase in costs, there is a possibility that wave power could make a valuable contribution to Britain's energy needs. At the same time, valuing nuclear power on the same basis clearly demonstrates that while it can be operated at reasonably high load factors nuclear plant will always be significantly cheaper.

Finally, it must be emphasised that the views in this Paper are based on still limited theoretical studies and small scale model tests and it will take several years of intensive study to confirm the prospects for wave power and many more to develop it on a commercial scale.

11. ACKNOWLEDGEMENTS

The information in this Paper is based on studies undertaken by the CEGB Research Division at their Marchwood Engineering Laboratories and is published with the permission of the Central Electricity Generating Board. The author also wishes to acknowledge the many valuable discussions he has had with other members of the CEGB and contributors to the DoEnergy study.

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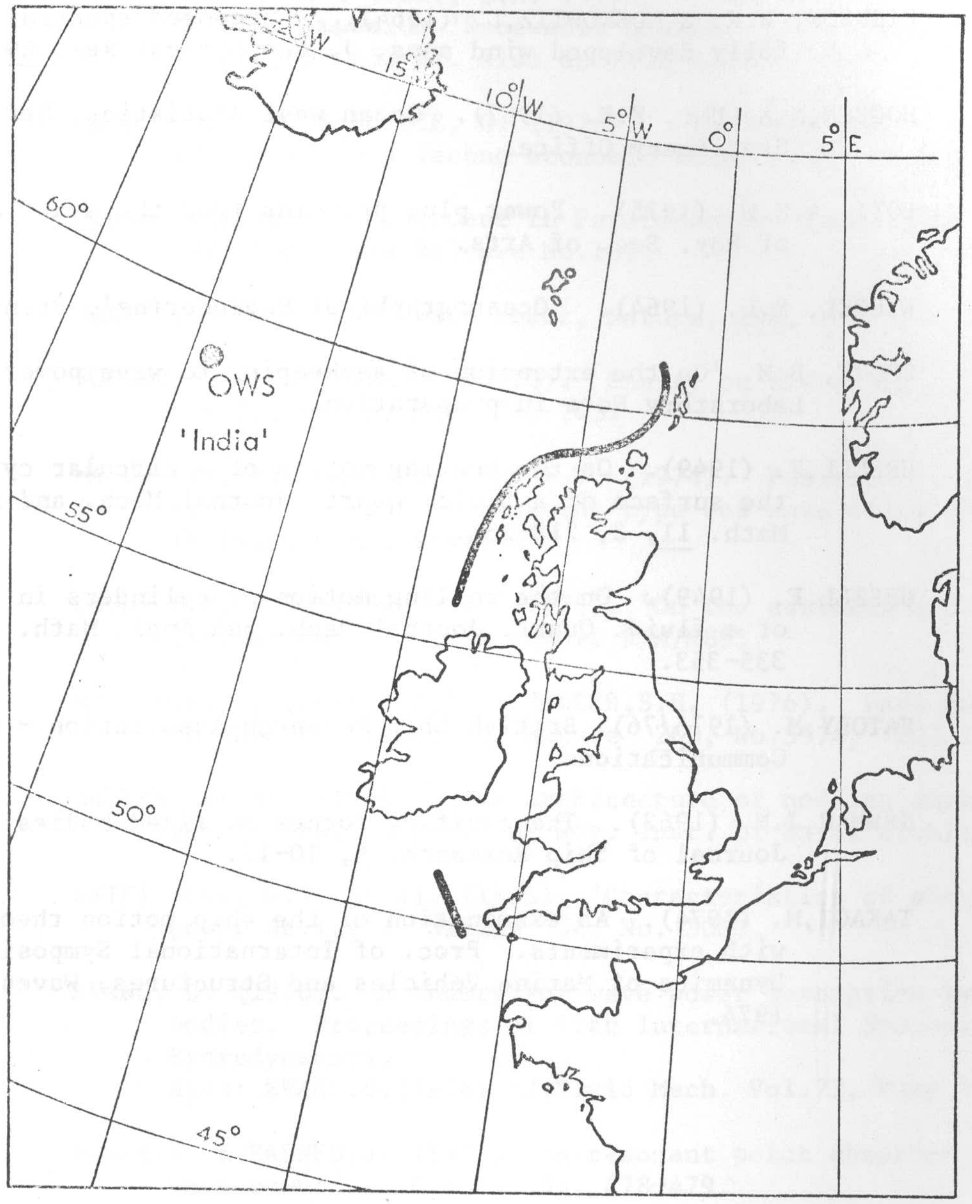

FIGURE 1. POSITION OF OWS 'INDIA' AND LIKELY WEST COAST WAVE POWER SITES.

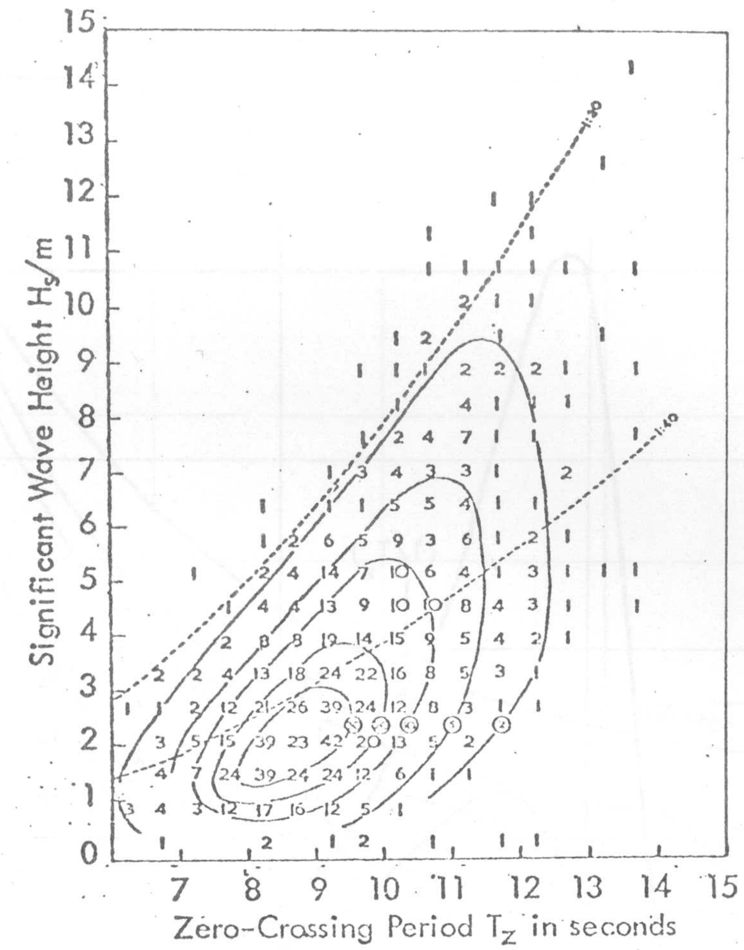

FIGURE 2. SCATTER DIAGRAM RELATING SIGNIFICANT WAVE HEIGHT TO ZERO CROSSING PERIOD FOR THE WHOLE YEAR AT OWS STATION INDIA SHOWING THE FREQUENCY/1000 OF H_s, T_z COMBINATIONS AND LINES OF CONSTANT WAVE SLOPES (1:20, 1:40)
(AFTER DRAPER 1967)

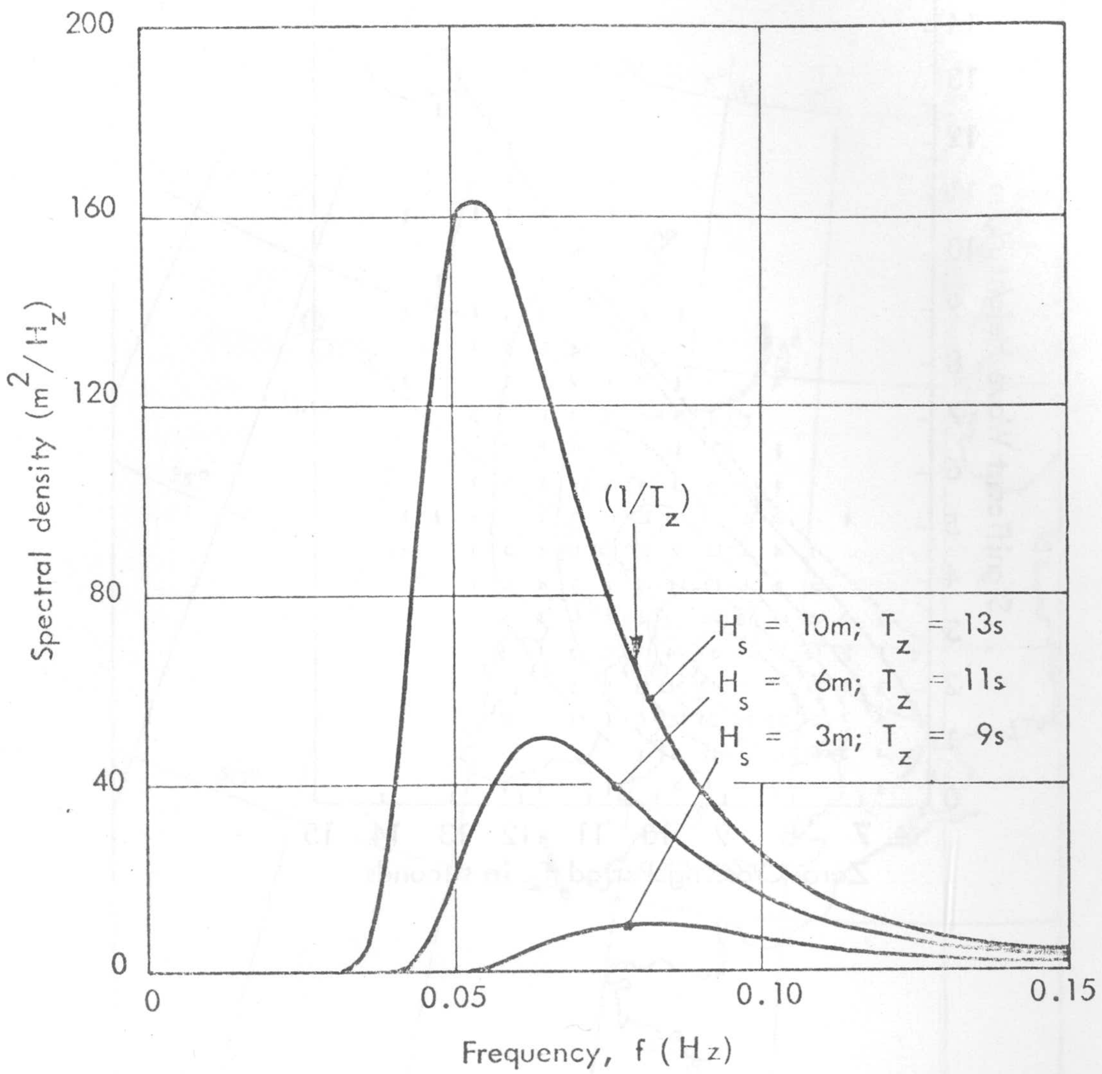

FIGURE 3. TYPICAL PIERSON-MOSKOWITZ SPECTRA

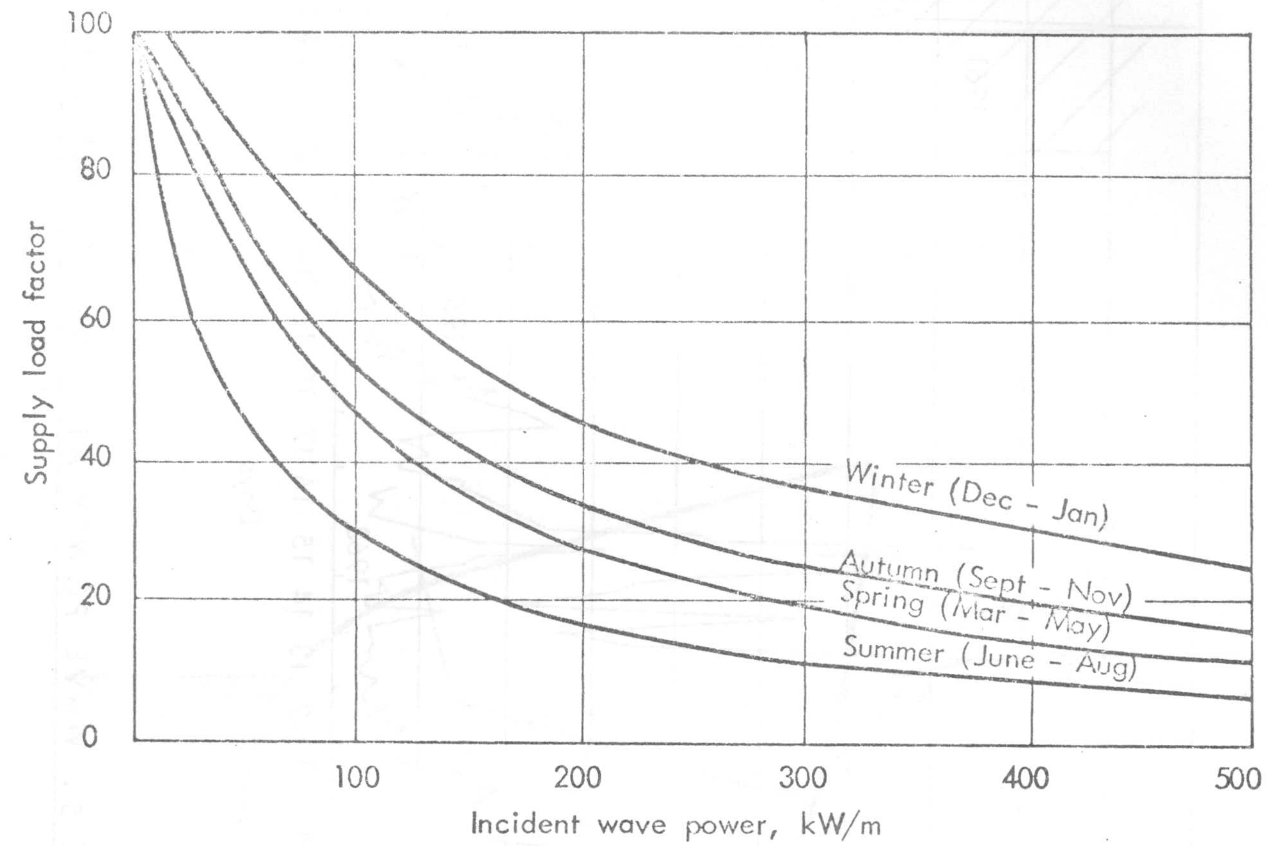

FIGURE 4. SUPPLY LOAD FACTOR CURVES FOR STATION INDIA (1955 - 1965)

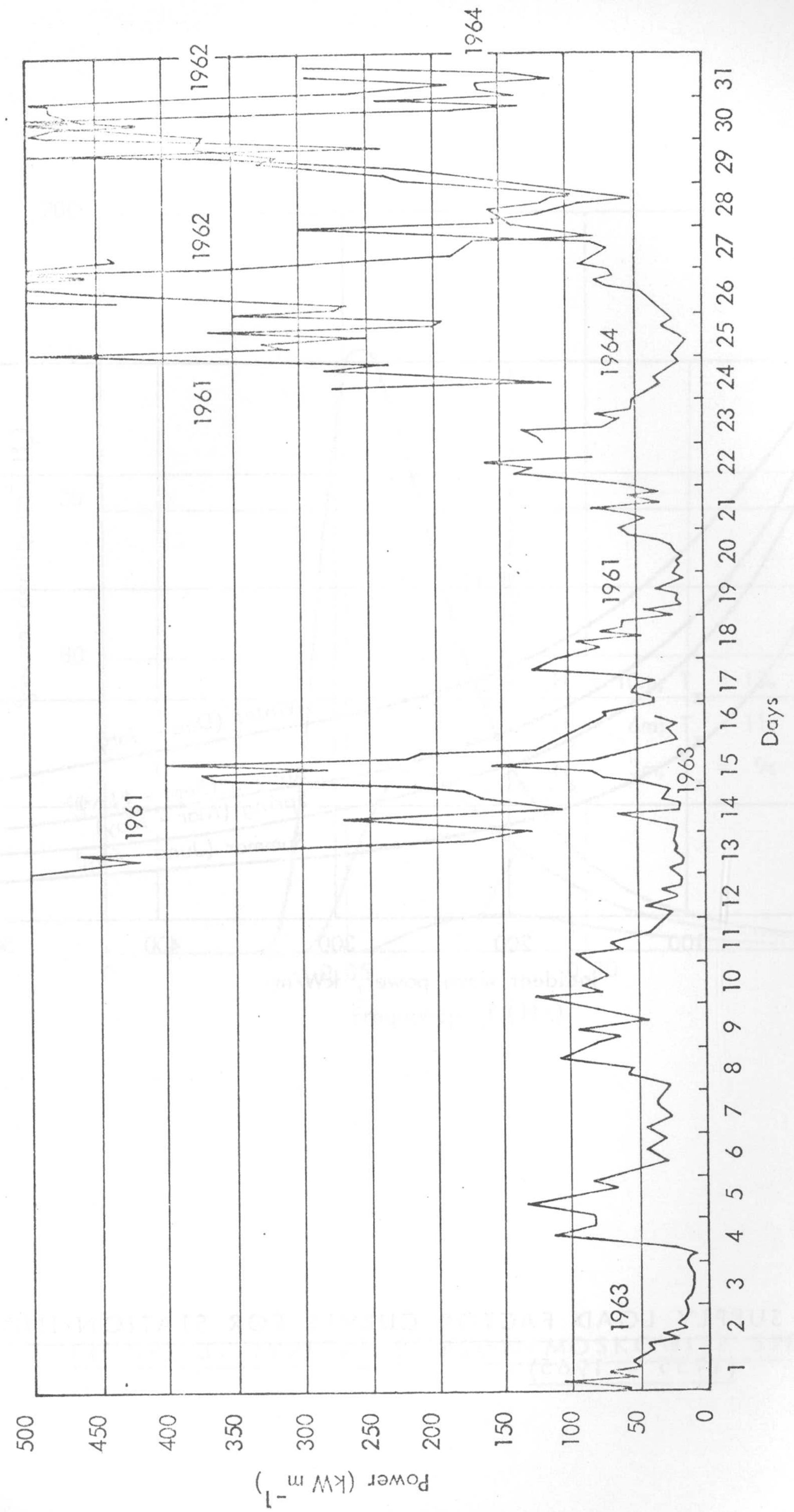

FIGURE 5. WAVE POWER AT INDIA - 'JANUARY'

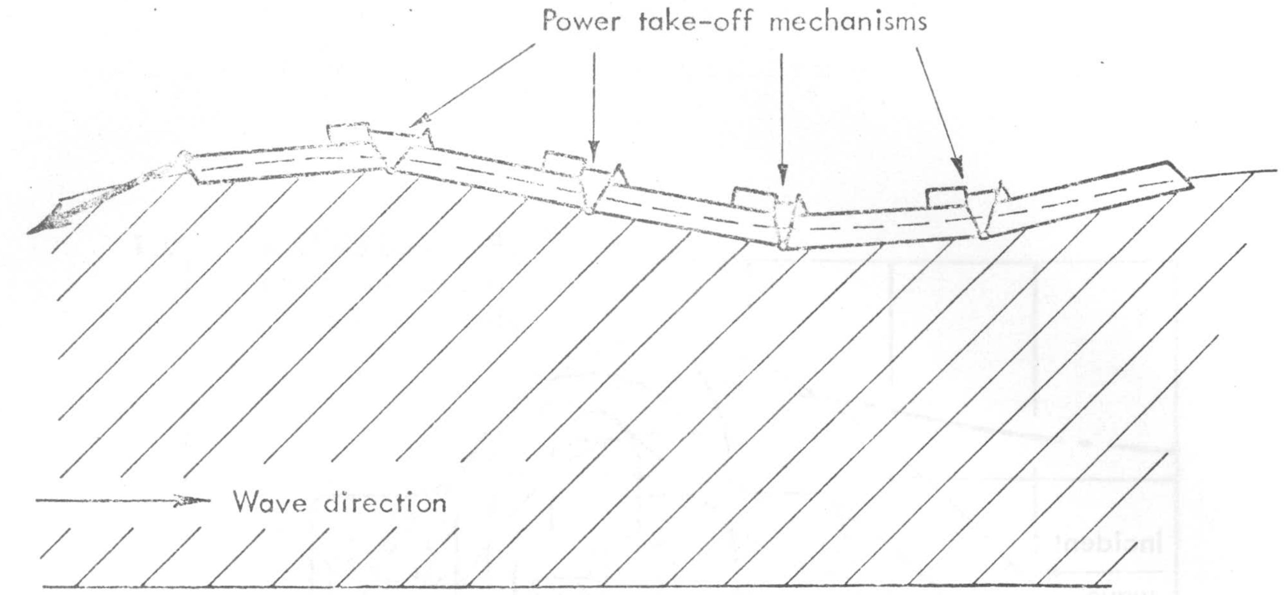

FIGURE 6. THE COCKERELL WAVE CONTOURING RAFT

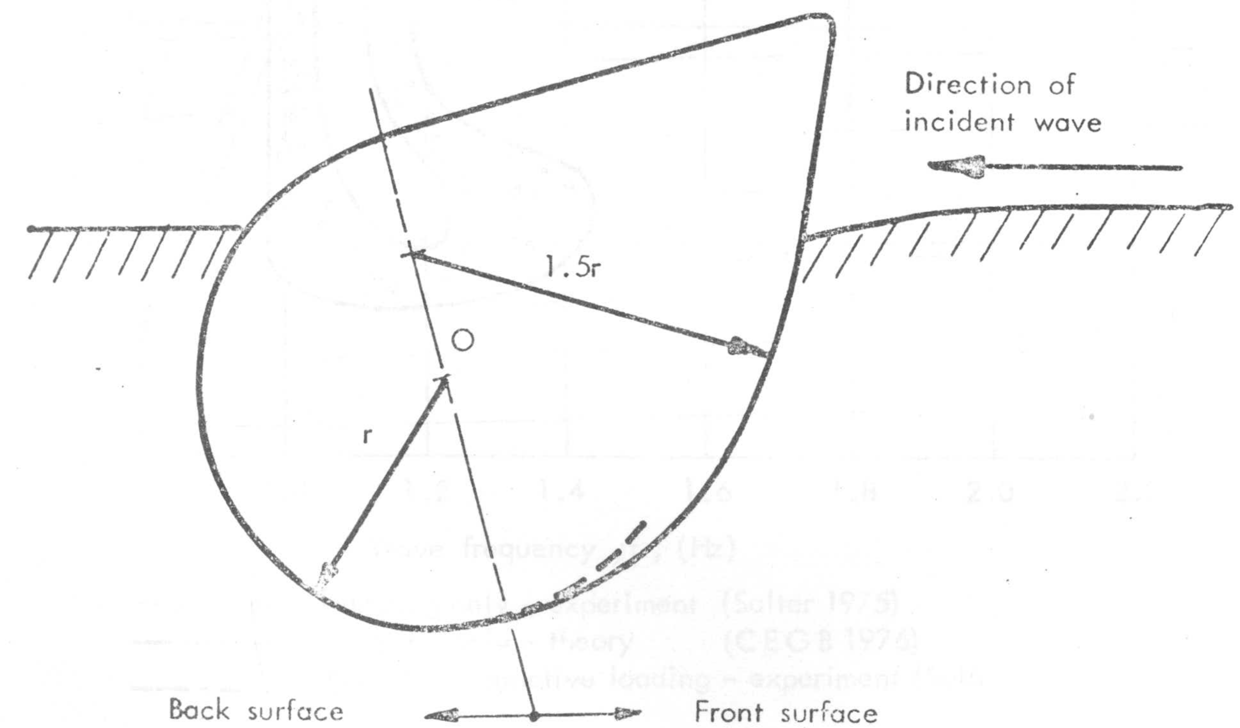

FIGURE 7. THE GEOMETRY OF THE SALTER CAM

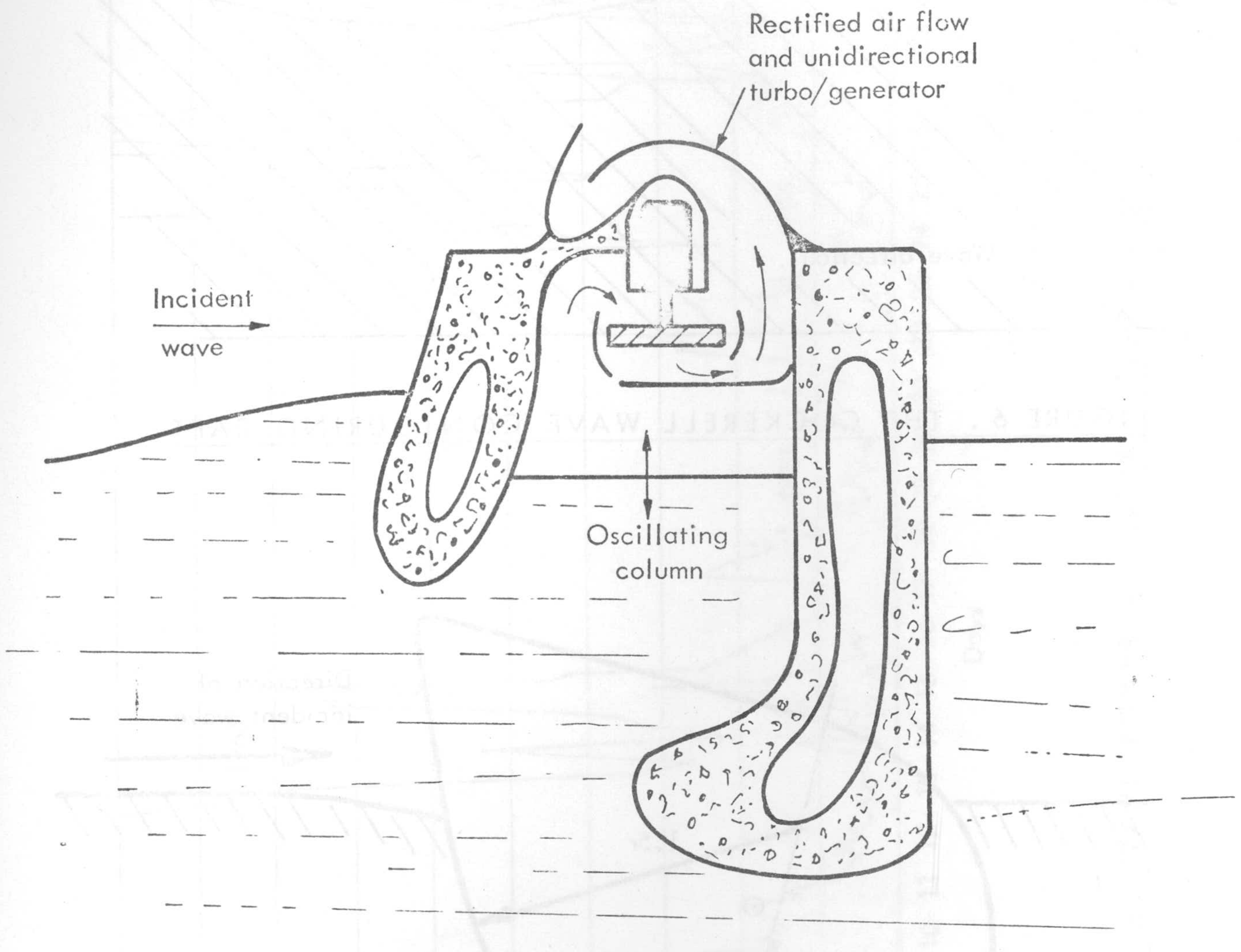

FIGURE 8. ADVANCED AIR BELL OF THE TYPE PROPOSED BY N.E.L.

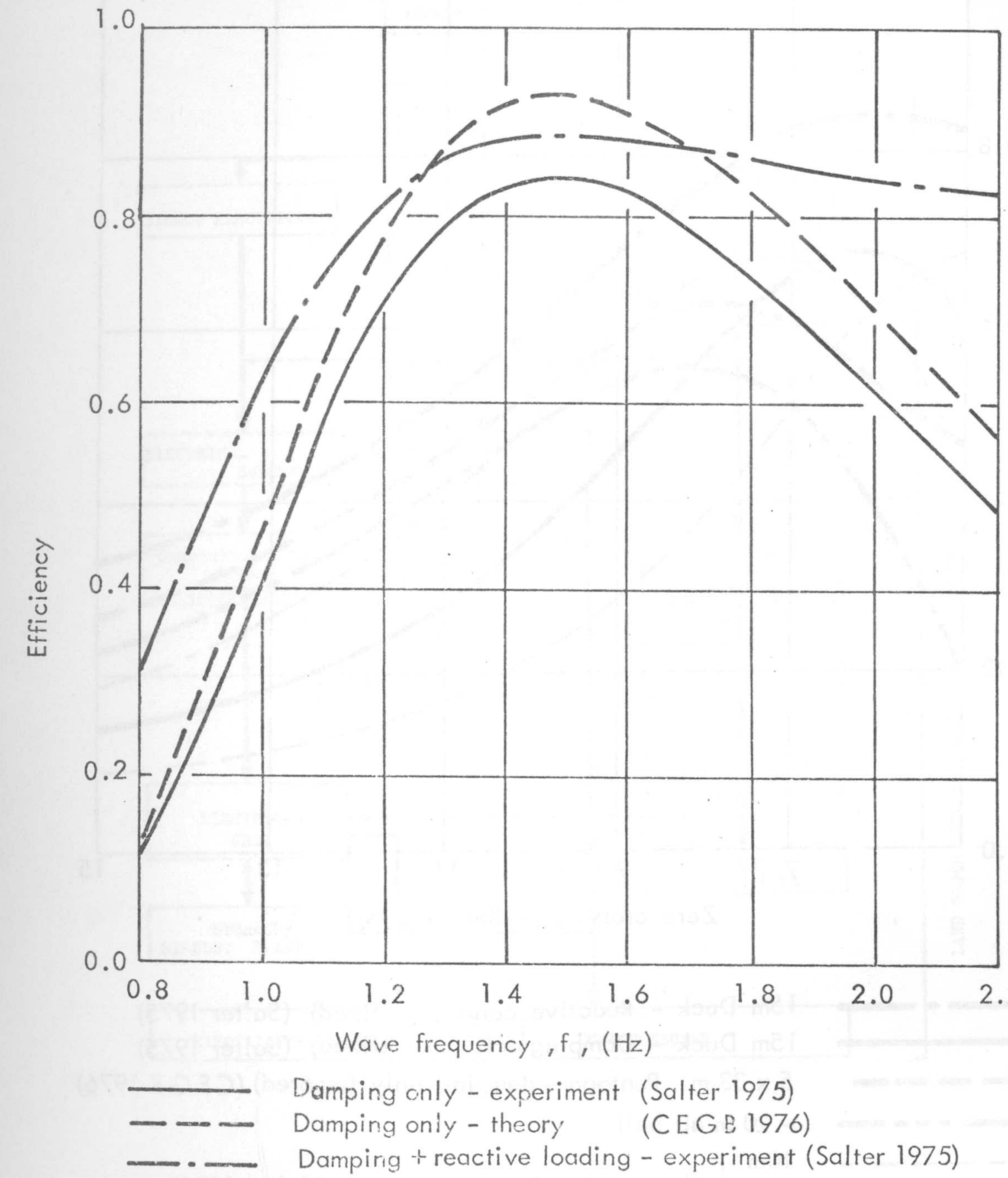

FIGURE 9. FIXED CENTRE DUCK PERFORMANCE.

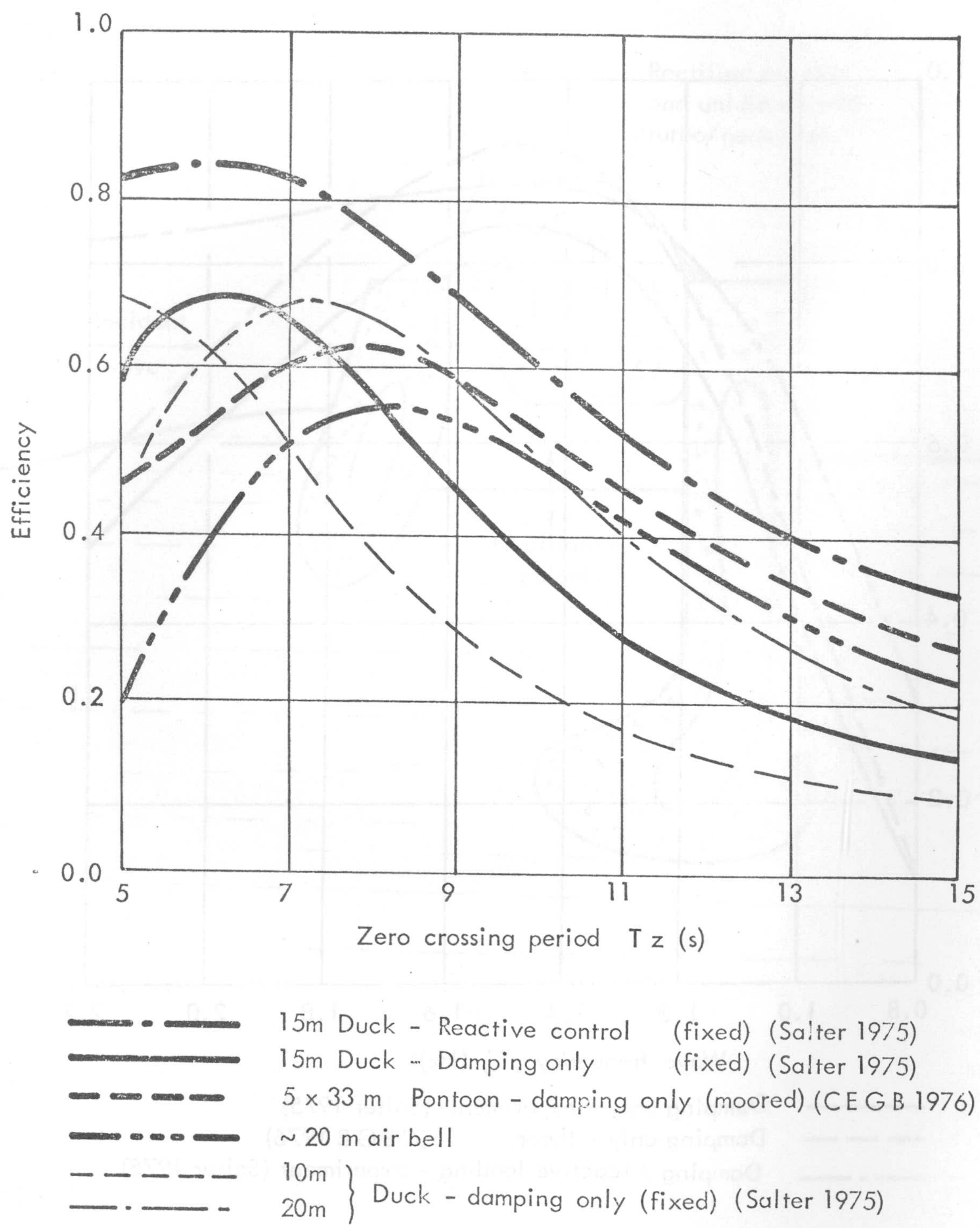

FIGURE 10. 'SEA PERFORMANCE' OF PREFERRED DEVICES.

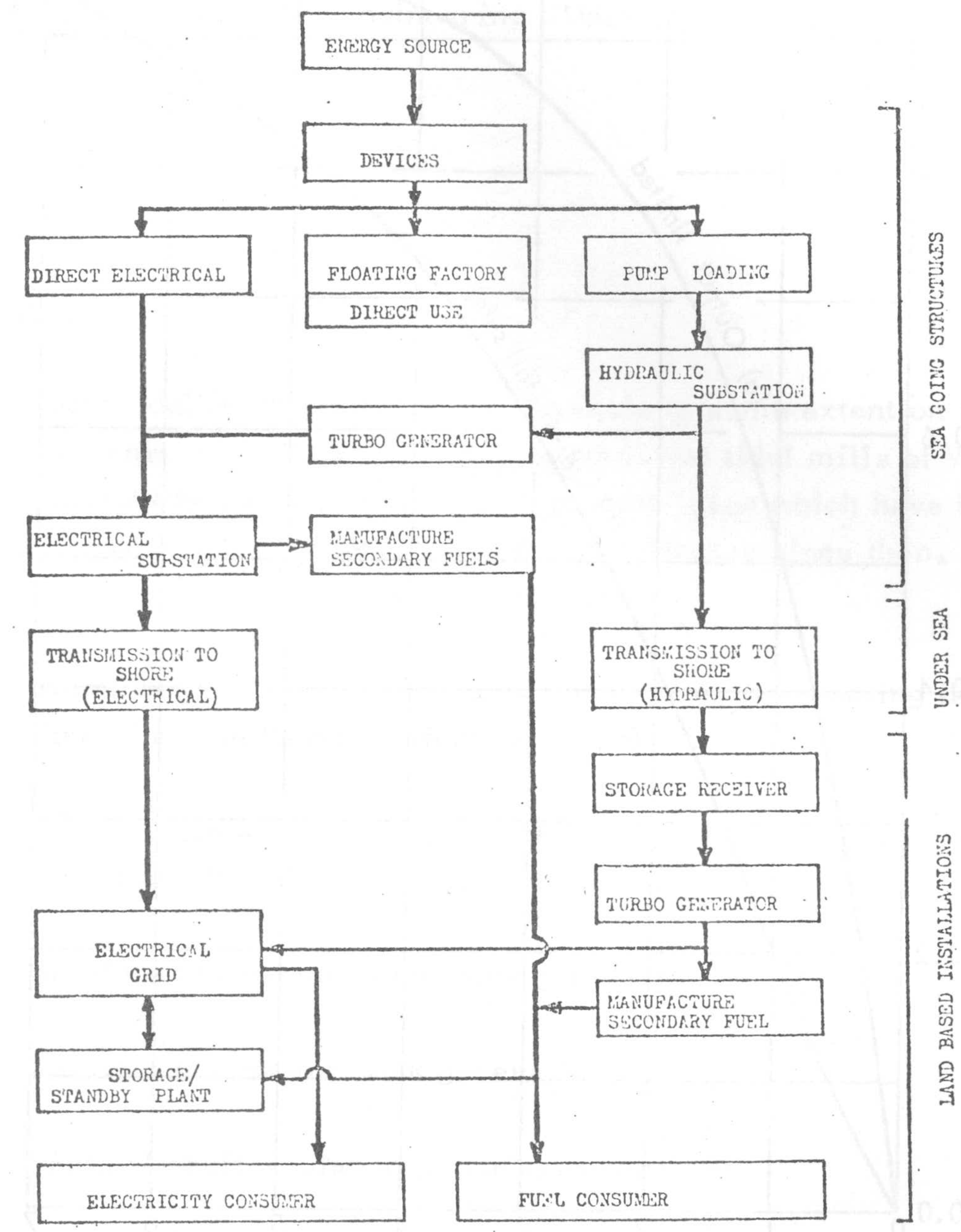

FIGURE 11 . POSSIBLE WAVE POWER SYSTEMS

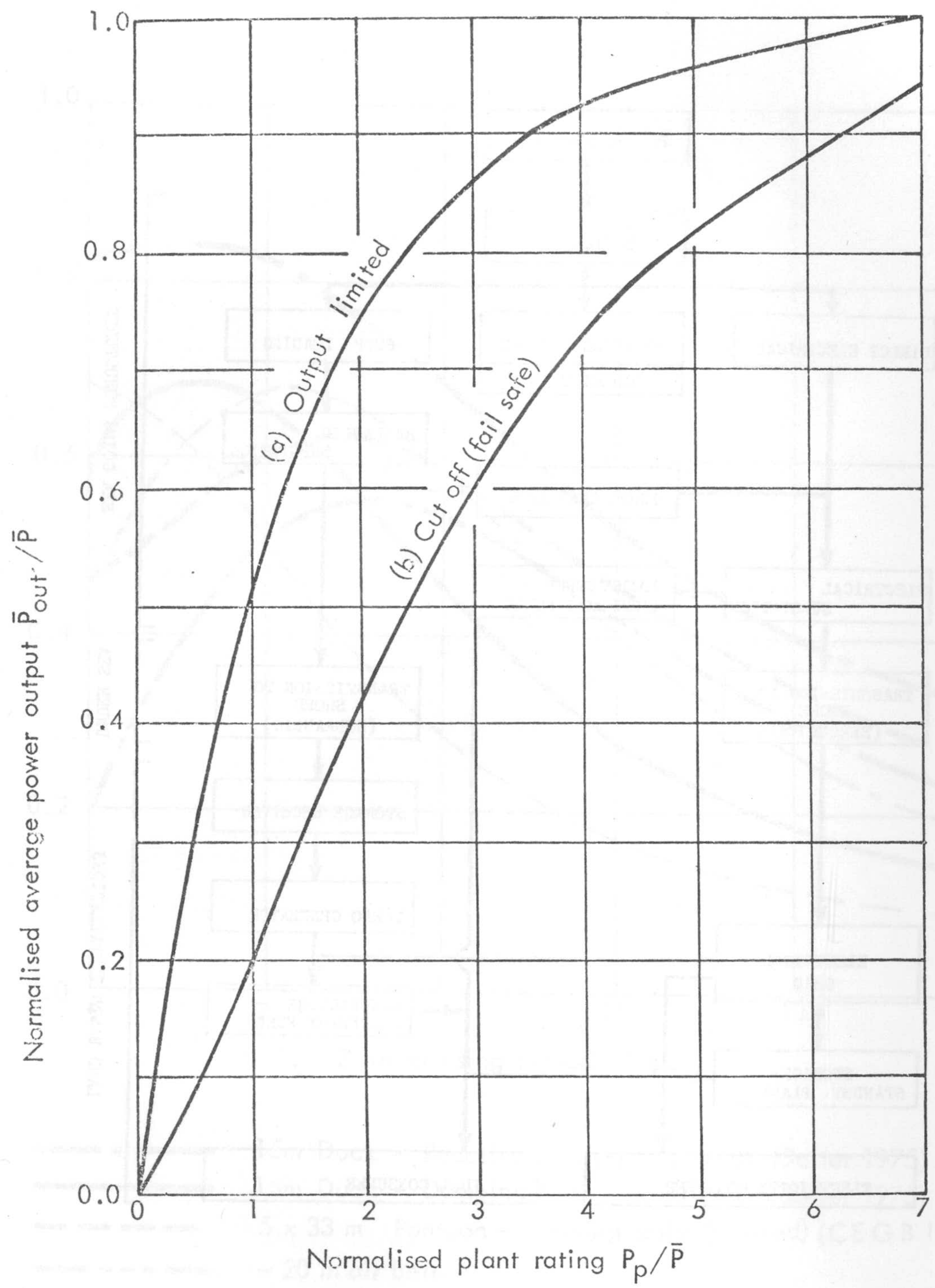

FIGURE 12. POTENTIAL POWER OUTPUT AS A FUNCTION OF THE PEAK/MEAN PLANT RATING ON A LINEAR WAVE POWER DEVICE/GENERATOR.

TIDAL POWER

Dr E M Wilson

Professor of Hydraulic Engineering : University of Salford : UK

1. Introduction

Any paper about tidal energy necessarily depends to some extent on the history of attempts to generate it, starting with the medieval tidal mills of Western Europe and examining some of the many ingenious ideas which have been propounded by engineering writers from many countries since then. These ideas have included, separately or in combination:-

a) single basin - ebb generation - turbo-generators acting in one direction (the "single-effect" scheme)

b) single basin - ebb and flow - turbo-generators acting in two directions (the "double-effect" scheme)

c) multiple basins and continuous generation

d) multiple basins and peak generation

e) vertical shaft Kaplan-type turbo-generators

f) horizontal-shaft "bulb"-type turbo-generators

g) horizontal-shaft propeller turbines

h) as (g) but with centrifugal pumps mounted peripherally to pump water at high pressures for Pelton-wheel turbo-generators

i) horizontal-shaft "straight-flow" turbo-generators with electricity generation by a perpheral alternator

j) propeller turbines driving air compressors for underground air storage and gas-turbine peaking generation

k) pumped hydro-storage in separate reservoirs overground and underground

l) pumped hydro-storage in estuarial reservoirs with assisted refilling by tides

m) electrically interlinked "single-effect" schemes

n) hydraulically interlinked "single-effect" schemes

o) single basin with two-way pumping/generating to produce guaranteed power

This is by no means a comprehensive list of ideas but probably includes those better-known. Hydraulic engineers will recognise Passamaquoddy in (d) and (e) and La Rance in (o). More esoteric varieties have usually been confined to technical articles and internal reports.

It will be clear, even from such a list as this that many people over a long time have wrestled with the problems involved, some successfully, others less so, and yet at the end of it all what is there to show for it? One well-publicised and documented 240MW scheme at La Rance which is no longer operated mainly as a power producer for which it was designed, but as an energy producer. It produced energy rather expensively to begin with but is rather more competitive now, of course, after ten years of operation, when the loans are being written down and alternative energy sources are becoming more expensive. In addition there is a Russian pilot plant at Kislayaguba, north of Murmansk in the White Sea, where one bulb-type machine produces some energy, while the structure housing it supplies data about the behaviour of materials in an ice-bound environment.

This is not a lot of practical result, it might be thought for so much ingenuity and effort expended. Such a view is understandable but only partially justifiable. The truth of the matter is that large-scale development of tidal-energy has had to await for technological developments to take place to make it possible. Firstly, the hydraulic turbine, then the electrical generator and then the development of sufficiently large electrical systems, with a variety of ways of meeting demand.

Finally, reliable methods of re-timing electrical energy in large quantities by its temporary storage in other forms were needed, together with high-voltage transmission systems.

The resurgence of interest in tidal energy in recent years has taken place because the methods and the markets are now more appropriate for it and to some extent because of the sudden awareness in the general public of the dangers of environmental damage from competing forms of energy production.

Tidal energy is one of the "cleanest" forms of energy; its production uses no land and has many side benefits. In short, the time for tidal energy development has just about arrived.

2. The oceanic tides and barrage effects

Ocean tides have a small range - usually less then 1m. Yet most of us will have seen much greater variations than that. This amplification is partially due to resonance, where a bay or estuary length and depth are such that a regular wave at the bay entrance builds upon the proceeding wave's effect, to produce increased amplitude at the closed end. Partially it may be due to the coastal configuration which funnels or channels the energy of a tidal wave into a smaller and smaller wave front and so a higher and higher wave.

However these two causes interact, it is a fact that a range of less than 1m in the Atlantic Ocean off Nova Scotia has developed to a 15m range at the head of the Bay of Fundy. On the other side of the continent, in Cook Inlet, Alaska, a 4m range at its entrance becomes 8m in Knik Arm, near Anchorage. In the Irish Sea, the mean range is 4.2m at Skomer Island at the mouth of the Bristol Channel, while at Avonmouth, the port of Bristol, it has increased to 9.4m. Clearly there are very large masses of water on the move and an opportunity exists to develop water power using turbo-generators.

One of the major questions then to be resolved is how much will the range of the tide be affected if a barrage is built closing off part of an estuary or inlet, and altering the discharge phase of ebb-flow by some hours. Since the energy to be captured is a function of the square of the range (or thereabouts), even comparatively small percentage reductions may alter the cost of energy appreciably.

Fortunately there are ways of tackling this problem, by mathematical modelling of the sea areas concerned. Such models have been developed in various countries but our own Institute of Oceanographic Sciences has been a pioneer and a model developed there of the Bay of Fundy and Gulf of Maine is currently being used in Canada to determine the effects of various power schemes in the Bay.

The effects can be quite large. Certain sites in Fundy have shown range reductions of over 20% though fortunately the most promising sites show much smaller changes and even slight increases. The Hydraulics Research Station has recently made a model of the Bristol Channel and Irish Sea out to the Continental Shelf edge to see what would happen with a Severn Barrage and I understand the results are showing small changes; some of them increases in range. It should perhaps be emphasised that the siting of barrage structures and operating modes may have an important effect so that the answer will not always be the same even for the same site.

3. Modern concepts of tidal energy generation and its integration into power systems

Most recent studies of possible tidal schemes have led to the conclusion that the most economical energy will come from single-effect schemes, that is, a scheme where the tide is allowed to fill up a basin through large sluice gates and the turbine water passages; is then retained at its highest level with closed sluices until sea level beyond the barrier dam has fallen to around mean sea level, when generation starts, and so produces its energy in varying amounts and at varying powers.

Each "slug" of energy is different from the foregoing one and separated from it by about six hours during which refilling is taking place.

Two-way and continuous generation schemes in the same place would produce about a quarter more and substantially less energy respectively, than the single-effect scheme but the evidence, though not conclusive, is that maximum value for capital invested, lies in the latter.

The "slugs" of energy will vary in size as the range of the tide varies from neap to spring tides over about 14 days, the ratio of energy outputs per tide being of the order of 1 : 3.

Since typical electrical system demands are higher in the daytime and early evening and lower during the night, so different generating plants are used, according to their characteristics, to serve particular blocks or components of the total demand. Such blocks may be continuous throughout 24 hours or confined to certain times, and may be at a constant or varying power level.

A tidal power-plant of the single-effect type generates energy for periods of limited duration, and at times related to the tides, and not at the same time each day. The amount of energy per tide varies with the cyclic variation of tidal range between springs and neaps. Since system demand does not correspond to a "raw" supply of this form, it is generally necessary to re-time delivery of the major part of the tidal energy by some form of energy storage.

It is perfectly posssible to design a tidal scheme to produce uniform blocks of energy for 12 hours per day if one uses a great deal of plant, two separate basins and a lot of system energy. The trouble is that it is very costly and does not remove the reliance on conventional (including nuclear) fuels since this internal retiming requires system energy and foregoes the generation of considerable amounts of "raw" tidal energy.

For the retiming of the output of any electricity generating plant a variety of methods may be employed. What must be emphasised is that such retiming facilities as are provided, are system facilities and are not linked to one plant only. It follows that it is system cost which is the final criterion by which the introduction of any new plant, including tidal plant, is to be judged.

It is often not appreciated that to meet the variations of electrical system demand, all power sources need a retiming capability if they work at less than 100% load factor. During 1972 studies on a tidal power site in the Bay of Fundy[1], TPC* considered the respective retiming costs in 1980 for the scheme's output, 10,500GWh per annum, supplied by tidal, nuclear and fossil-fuel energy. The results, which are indicative rather than definitive, are shown in Table 1 and illustrate that at low load factors, (i.e. in the less than 30% range) the retiming capacity required and costs of operation for each source are of the same order.

Energy Source	Demand L.F.	Retiming Annual Costs Capital	Operation
		$\$ \times 10^6$	
Tidal	25	66.2	37
	50	52.6	32
	100	35.4	30.5
Nuclear	25	40.0	34.6
	50	16.8	19.2
	100	0	0
Fossil	25	40.0	34.6
	50	16.8	19.2
	100	0	0

Based on an equal mix of p.s. hydro and compressed air storage giving operating inputs per kWh generated of 1kWh + 2375 BTU: assuming levelised fuel costs (1980) @ 8% for 30 years, of $2.04 per million BTU.

TABLE 1

It may be instructive here to insert a note about La Rance, the French tidal power station commissioned in 1966. This scheme was designed with a single-basin equipped with 24 10MW pump-turbines to provide power on a few hours notice. Pumping employs system energy to alter the reservoir water level, up or down, to ensure power capacity at the required time. The machines and power station are expensive and latterly have been showing signs of premature ageing. The production record of the station is shown in Table 2.

	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
Gross Production GWh	3,067	208,152	418,556	463,709	494,759	500,989	551,401	559,254	597,841	517,108
Pumping Consumption	120	9,118	24,513	38,041	39,873	42,029	59,474	62,160	90,870	35,622
Nett Production	2,947	199,034	394,043	425,668	454,922	458,960	491,927	497,094	506,971	481,486
Coefficient of Utilization %*	-	-	72.5	78.3	83.6	84.0	90.4	91.4	93.2	88.4
Mean Machine Availability %	-	-	77.0	85.0	93.5	95.0	93.9	95.2	95.5	85.8

* expressed as percentage of theoretically - available nett production 544GWh/year

TABLE 2 - Production record of La Rance t.p.s.

The retiming facility at La Rance is the flexible pump-turbine machinery. The question is - are there cheaper and more efficient ways of obtaining the same results on the system? Table 1 seems to indicate that by trying to cater only for demand in the 15-30% load factor range, by going for maximum energy generation and using system retiming facilities (slightly augmented), tidal energy is moving into a competitive position with alternative energy sources.

4. Modern construction concepts

The Rance station was built in a cofferdam which took two years to build and 30% of the civil engineering cost. So if bigger and longer barrages are to be built - a way must be found of avoiding these very large cofferdams. Such a way has arisen out of the use of floating caissons, of which the British Mulberry Harbour caissons built in 1944 for the invasion of Europe were an early example. Some of these caissons were used by the Dutch after the war to close the gaps in the dykes made by both sides during the battles in Flanders and Holland. Then after the disastrous 1953 North Sea floods, the Dutch devised the Deltaplan - the damming of the sea-arms of the Rhine delta.

To close these estuaries many new hydraulic engineering techniques became necessary. The gradual filling method was one such - another was the use of culvert caissons used on several of these closures in the 1960's. The culvert caisson is essentially a large floating concrete box which can be sunk onto a prepared foundation, have its sides removed and allow tides to ebb and flow through it until the whole gap is covered. Then all at once and right across the gap the gates may be closed. Meanwhile others were using the techniques of float-in construction. It has become a standard method for putting lighthouses out at sea and for crossing estuaries with road tunnels. So it came as no real surprise to find the Russians using it for their pilot tidal power plant at Kislayaguba near Murmansk in 1969.

The Russians built the power station in a building dock, fitted it with turbo-generators and floated out the whole unit, having first dredged away the dock bank. The unit caisson was towed to its site with additional buoyancy tanks along-side and settled down into position on a prepared base. There is no doubt that this is the preferred method for future tidal power stations and modern station designs, like Fig 1, are all based on this float-in type of construction.

This caisson is a very large affair indeed but even it is outclassed by others already constructed or under construction - notably the Ekofisk oil storage caisson built in a fjord at Stavanger and floated out 150 miles into the North Sea, the Condeep platforms constructed in a Norwegian fjord and floated out to station in the North Sea in 1975 and even larger structures being built in Scotland. The tidal power engineers' apparently daring ideas of only a decade ago have already been far surpassed by the oil-men.

The caisson concept of construction has been extended to the other parts of the barrage as well as the power house and Fig 2 shows a sketch design for one of the proposed refill sluices for the Knik Arm scheme in Alaska. Connoisseurs of tidal power schemes will recognise in this structure a direct line of descent from Passamaquoddy designs, though any other similarity to that scheme is absent.

5. Turbo-generating machinery

The French bulb turbine as fitted in the Rance power station was designed to act both as a turbine and a pump, and to act in either mode in either direction. Being a sophisticated machine and a prototype installation it was an expensive solution. It is now, of course, a well-tried machine and has been extensively adopted in its low-head turbine role in conventional hydro schemes. It remains expensive, however, and there is recent evidence from La Rance that the life of the machines may be only half the originally-designed 30 years.

One way of economising is to use a tidal scheme only as an energy producer thus avoiding the pumping mode and the reversible-pitch turbine blades, and by generating only in one direction, avoiding a draft-tube on the upstream side. This gives cheaper energy but does not provide firm power and so one has to look at the whole system to see if storage can be provided in other ways.

Another way to cheapness may be through the use of different machinery. One solution proposed is the straight-flow turbine which was developed to a considerable extent in England by English Electric but has been independently developed and is now offered as a low-head solution under the name Straflo, by the Straflo Group - a partnership between Escher Wyss of Zurich and Straflo Ltd, London.

In this machine the generator rotor is carried peripherally on the turbine blades and the electrical generator is separated from the water passage by a special seal which has been the subject of intensive development. Even more remarkable is the bearing concept since in its propeller form the Straflo turbine can be built without any central shaft at all, all the bearings being hydrostatic pads on the outer rim. This machine offers large potential savings because of its compactness and cheaper civil construction cost and can be built in the sizes required for tidal energy development without difficulty.

Fig 3 shows a sketch design of this machine, for which a first order has been obtained.

The Straflo machine can also be built as a pump-turbine though, like the "bulb" at considerably greater expense. The choice of machinery is intimately tied-up with the mode of operation of the scheme and the economic value of power and energy on the system.

6. Outputs and costs

The writer has been involved in estimating for two tidal schemes for which detailed and reliable cost estimates have been made in the last decade – one in 1968 and one in 1971. The problem is to update these in the light of cost inflation.

The simplest approach is to use the Retail Prices Index and on that basis 1968 prices should be multiplied by 2.5m and 1971 prices by 2.1 to obtain 1976 prices.

In 1968, the Bristol Channel scheme in England[2] was estimated to have an annual cost, at 10% per annum interest rate, M£35 for an output of 10,500GWh. The 1976 equivalent is M£87.5 which gives an energy cost of 0.83p/kWh. In the light of recent work, the annual energy output is likely to be greater than 10,500GWh, probably nearer 13,000GWh, at a less than proportionate increase in capital cost.

In 1971, the Economy Point scheme in the Bay of Fundy[3] was estimated to cost M$725 at 1968 price levels for an output of 11,000GWh. Using 10% interest rate, the annual cost was M$80, giving a unit cost in 1976 of 1.53 cents/kWh.

These two schemes are fairly similar in size of sea area, water depth, tidal range and installed capacity. The two estimates were made independently in UK and Canada, so the agreement on energy cost is very satisfactory. Even allowing for substantially increased contingency costs, it seems that tidal energy could have been available at no more than 1.0p/kWh in 1976.

If one builds a tidal power station, all the energy will be used and so tidal energy all has one price. This is untrue of any other system except perhaps geothermal energy. Even hydro-electric energy cost varies with rainfall. The cost of energy from various sources is computed in Table 3 and shown on Fig 4 and superimposed is the probable price range of tidal energy from the schemes mentioned.

Short of doing a complete costing of a whole system, with and without tidal or wave energy, it is clear that the decision as to how the capital cost of the storage facility is to be allocated is critical. For example: nuclear energy is cheapest at maximum load factor (say 30%) when from Fig 4 it costs about 1.43p/kWh. If that energy is being used to charge a storage plant it compares with tidal energy at around 1.0p. Oil-fired energy at 80% load factor would be costing 1.78p/kWh.

(1) Type of station	(2) Heat cost p/therm	(3) Cycle efficiency %	(4) Incremental cost of energy p/kWh	(5) Annual incremental energy cost £/kW/yr at 100% LF	(6) Specific cost £/kW	(7) Years to construct	(8) Total compounded interest during construction £/kW	(9) Total Capital cost £/kW	(10) Annual charges £/kW/yr	(11) Annual charges and annual energy at 100% LF £/kW/yr
Residual fuel oil	12.4	35	1.21	106.0	230Ø	5	50.0	280.0	30.8	136.8
Coal	10.9	35	1.07	93.7	280Ø	5	60.8	340.8	37.5	131.2
Straight gas turbine	15.7	28	1.92	168.2	135+	2	6.75	141.8	15.6	183.8
Compressed air storage gas turbines and oil reheat	-	-	1.67 (0.81)	146.3 (71.0)	150+	3	15.4	165.4	18.2	164.5 (89.2)
Compressed air storage gas turbines and heat store	-	75	1.62 (0.30)	141.9 (26.3)	175+	3	17.9	192.9	21.2	163.1 (47.5)
Hydraulic Pumped storage	-	72	1.69 (0.32)	148.0 (28.0)	155+	6	43.5	198.5	21.8	169.8 (49.8)
Nuclear SGHWR	-	-	0.23	20.1	540*	8	227.9	767.9	84.5	104.6

NOTES:

1) Figures in brackets refer to energy costs for compression of air or pumping of water using base load nuclear SGHWR plants.
2) This table is used for drawing Fig 4 and employs limiting values which do not necessarily reflect real conditions.
3) Interest during construction is assessed on a linear capital expenditure from beginning of second year to end of construction period. The interest is compounded to commissioning date.
4) Capital costs have been calculated at 1974 prices multiplied by 1.5.
5) Costs: Ø Based on Ref 4: + author's estimate: * ex Ref 3.
Residual oil at £51/ton (£6.9 barrel): coal £26.8/ton of C.V. = 11,000 Btu/lb:
distillate oil £68.6/ton of C.V. = 19,500 Btu/lb.
Interest at 10% + 25 yrs amortization = 11% per annum.

TABLE 3

Generally speaking tidal energy is competitive in cost with oil and coal-fired energy at all load factors, but cannot match incremental nuclear costs as, at present, predicted. Even if nuclear fuel prices were to rise substantially and interest rates to fall, it seems unlikely that sea-energy will become cheaper than these incremental costs, but here it has been argued that it is unreasonable to design and build nuclear plant to fuel pumped-storage plants with part of their output, and to exempt that part only from capital charges. On the other hand, tidal energy cost is likely to be inflation-proof, having no fuel and a very small labour component. Also it is environmentally unobjectionable and tidal barrages have many advantages besides their energy-producing role. They provide estuary road crossings, they exclude tidal surges and the flooding of riparian land and they improve navigation into estuarial ports - and finally there is no danger of the depletion of the energy source in the foreseeable future.

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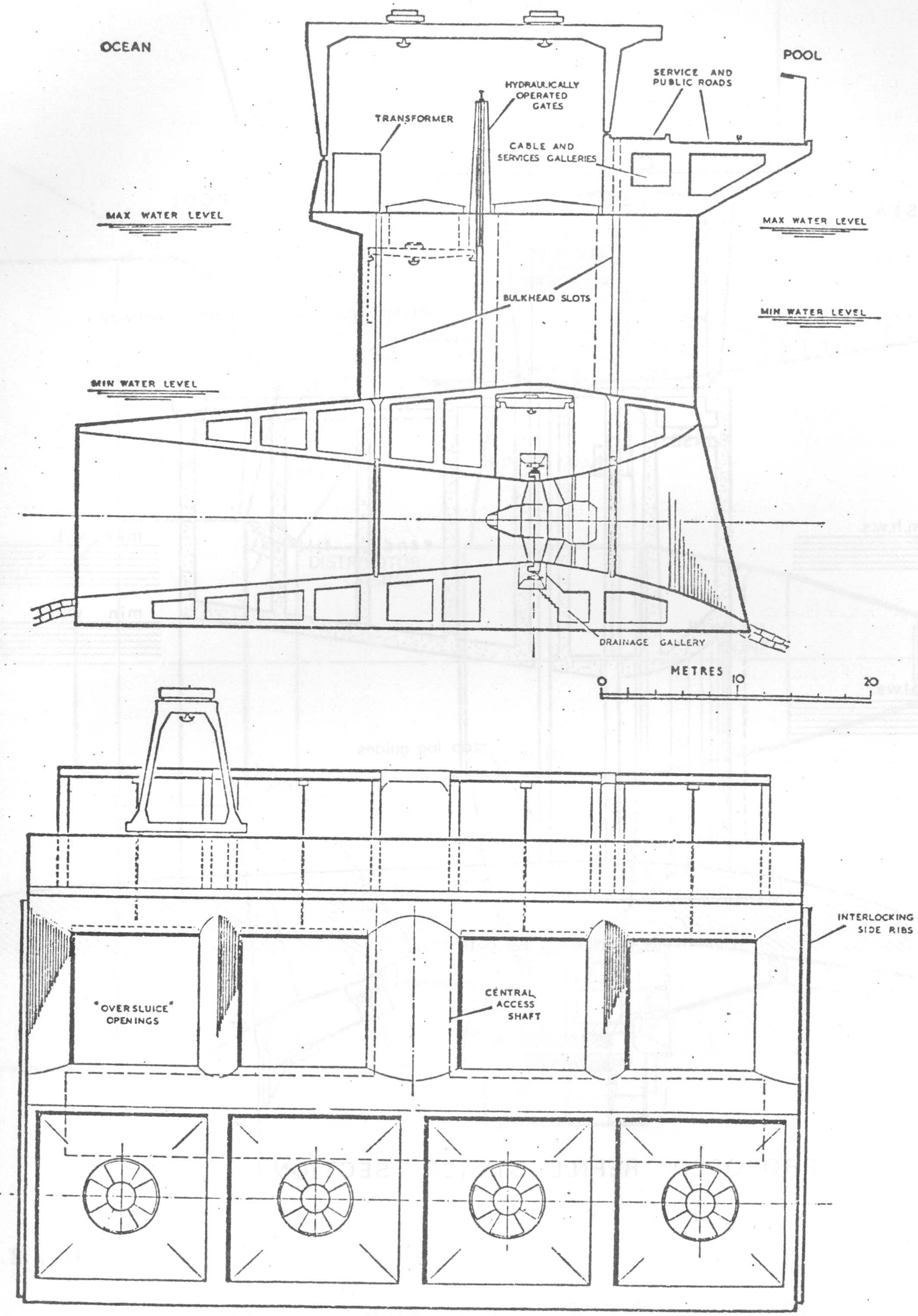
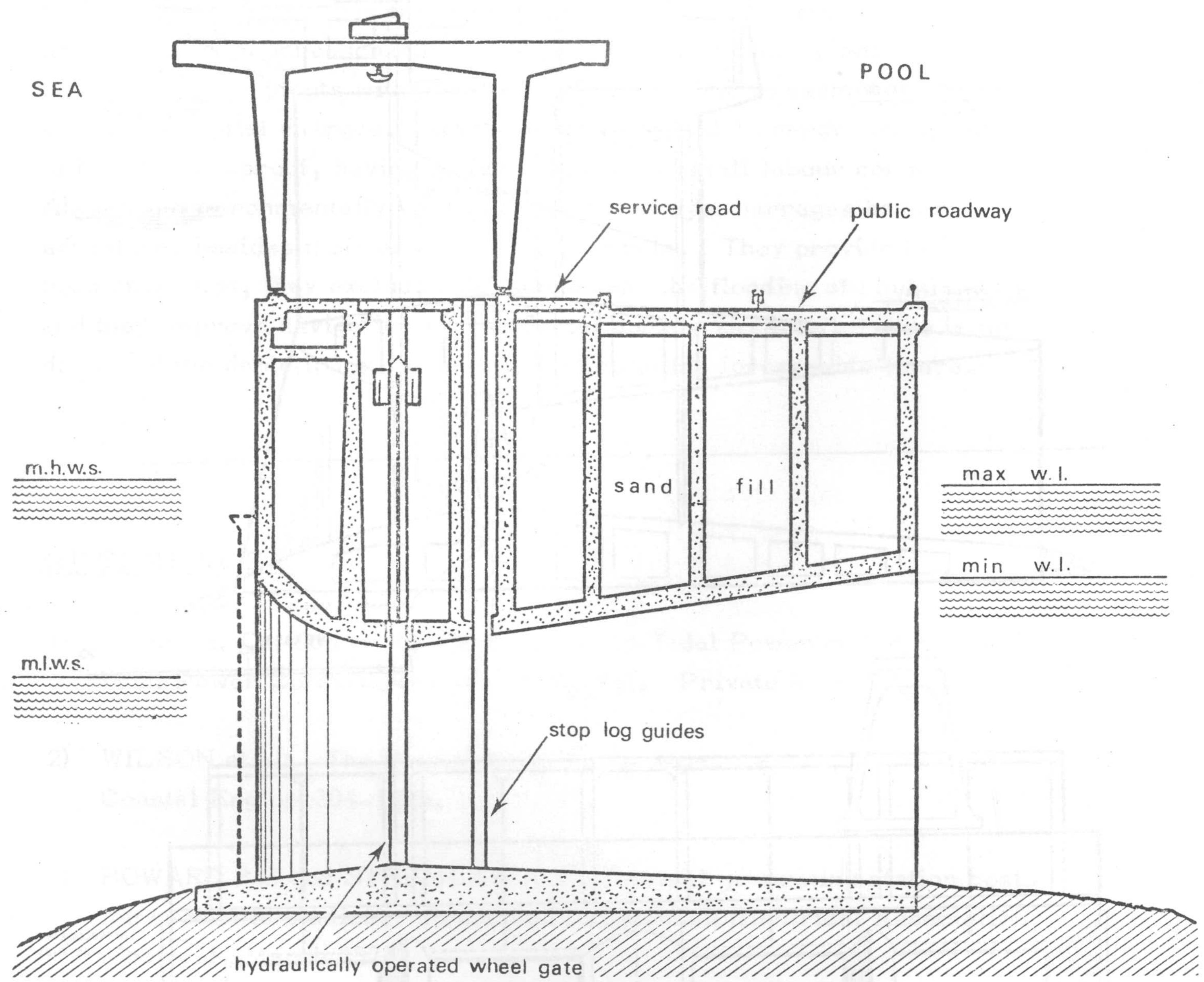
4) Select Committee on Science and Technology. Part IV (1074-75) p.15

* TPC is - Tidal Power Consultants Ltd and is a consortium of Montreal Engineering Co and Shawinigan Engineering Co of Montreal, Harza Engineering Co of Chicago and Engineering & Power Development Consultants Ltd of Sidcup, Kent.

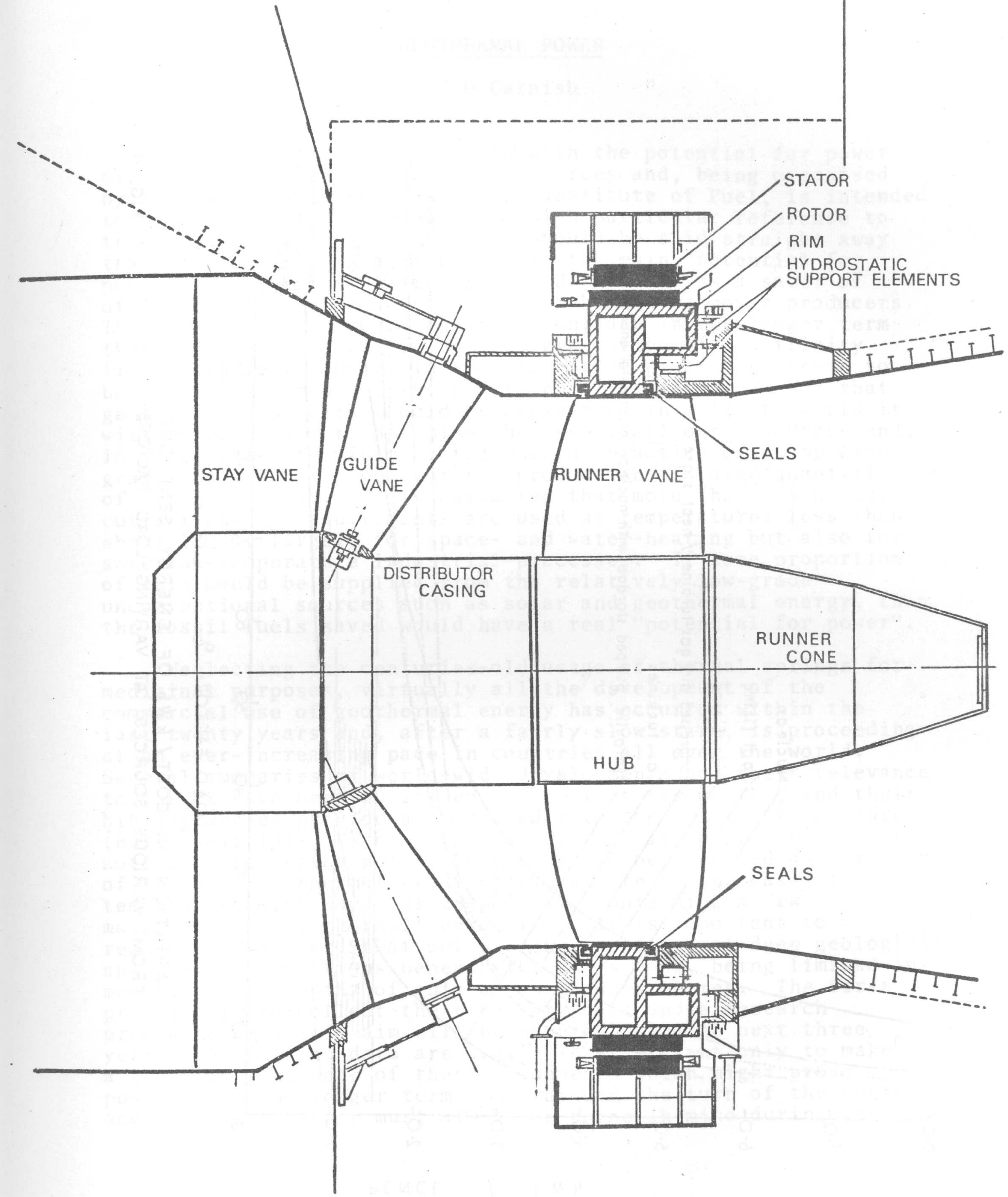


FOUR TURBINE CAISSON FIG. I.

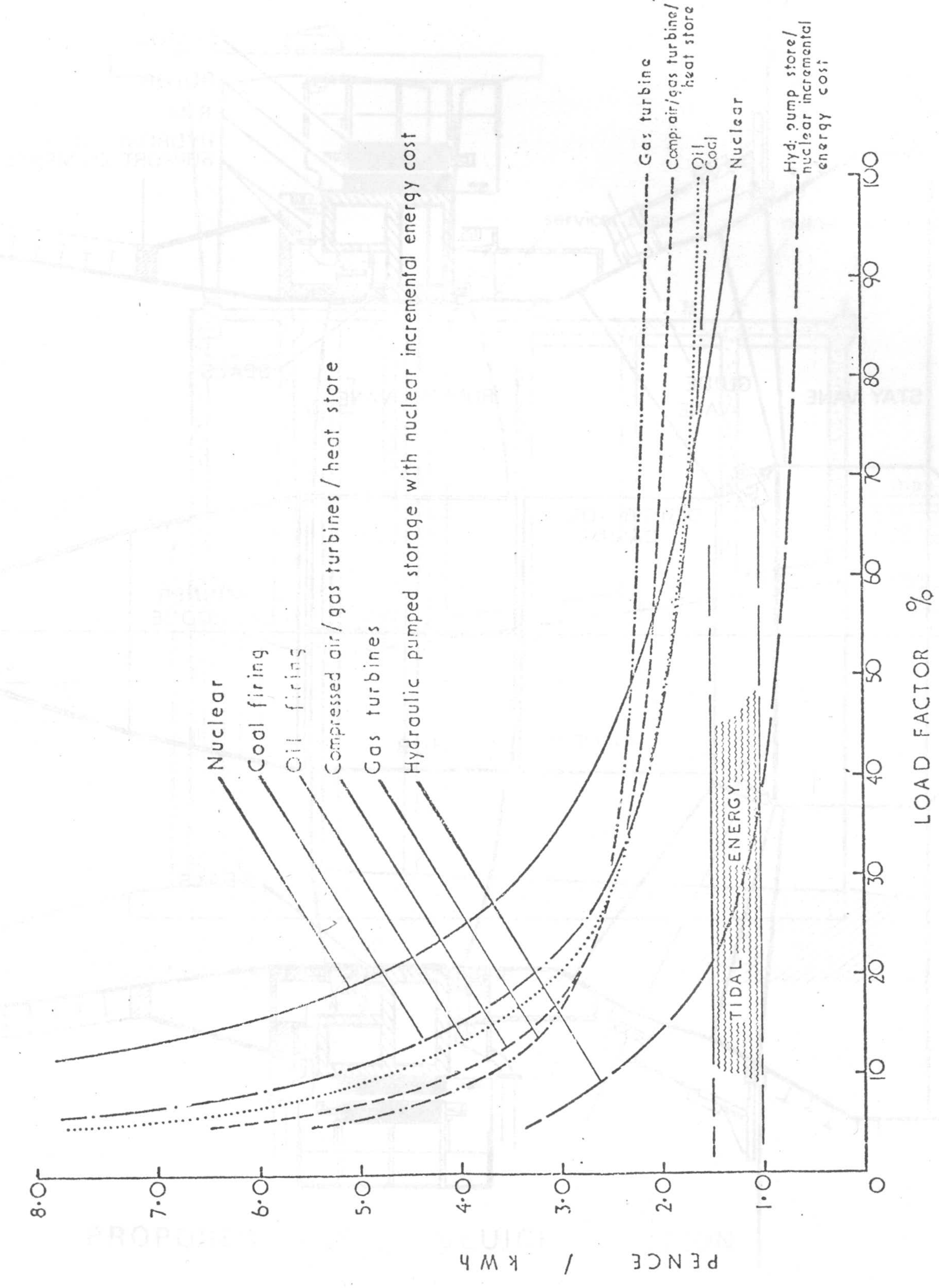


PROPOSED REFILL SLUICE SECTION

FIG. 2.



STRAFLO TURBINE GENERAL CROSS SECTION FIG 3



VARIATION IN COST / kWh OF ENERGY SENT OUT FROM VARIOUS SOURCES AT VARYING LOAD FACTORS

FIG. 4.

GEOTHERMAL POWER

J D Garnish

This Symposium is concerned with the potential for power of various unconventional energy sources and, being organised by the South Coast section of the Institute of Fuel, is intended to investigate the possibilities with particular reference to the southern half of the UK. It should be said straight away that, in the opinion of the author, the main "potential for power" of geothermal energy in the UK will be as a saver of other high-grade fuels which are in themselves power producers. This is perhaps an oversimplification, and in the longer term there may be prospects for direct generation of electricity from geothermal sources in the UK, but at present it seems to be a fair statement of the position. This is not to say that geothermal prospects should be neglected; in a finite world it will be necessary to optimise the use of all our resources and, in particular, to minimise the current practice of using high-grade fuels such as oil for the production of large quantities of low-grade heat. It is estimated that more than 40% of our current energy requirements are used at temperatures less than about 120°C, largely for space- and water-heating but also for some low-temperature industrial processes. If some proportion of this could be supplied from the relatively low-grade unconventional sources such as solar and geothermal energy, then the fossil fuels saved would have a real "potential for power".

Neglecting the centuries-old usage of thermal springs for medicinal purposes, virtually all the development of the commercial use of geothermal energy has occurred within the last twenty years and, after a fairly slow start, is proceeding at an ever-increasing pace in countries all over the world. Several summaries of world-wide developments and their relevance to the UK have been published in the last few months, and their bibliographies provide a good lead into the earlier literature (Bullerwell 1976, Garnish 1976 a, b). It is sufficient here to note that in geothermal terms the UK can be regarded as a region of 'normal' geothermal gradient (ie a rate of increase of temperature with depth of 25-30°C/km) containing a few marginally 'semi-thermal' anomalies. It is important to recognise, however, that our present knowledge of deep geological and thermal conditions beneath the UK is poor, being limited in many areas to depths of only a few hundred metres. The first priority is to collect the necessary data and a research programme with this aim will be mounted over the next three years. Sufficient data are available at present only to make a tentative estimate of the developments which might prove possible in the longer term (say, around the turn of the century) and this uncertainty must always be borne in mind during the

The views expressed in this paper do not necessarily represent those of the Department of Energy or the Energy Technology Support Unit, Harwell, by whom the author is employed.

discussion which follows.

Up to the present time, most geothermal developments in the world have exploited naturally occurring steam fields. In a geologically stable region like the UK, far removed from the tectonic plate boundaries, the possibility of locating such a resource can be discounted (Garnish, 1976 a). The types of resource that could exist, however, may be divided into aquifer sources and 'hot dry rocks'. In either case, exploitation would amount to mining the heat contained in the earth's crust and, as such, the extent to which it might be able to contribute to the nation's energy needs is subject to both technical and economic constraints. At least in the foreseeable future, it appears that the economic criteria will be the controlling factor on both national and local levels. This may be demonstrated by the following broad illustration, some details of which will be discussed at greater length later in this paper.

The maximum depth from which geothermal energy can be exploited in the crust depends on the technology available for the drilling of deep wells. In the oil industry, well depths of 4.5-6 km are being achieved almost as a matter of routine, the deepest wells so far achieved have been completed at depths a little over 9 km, and the probable limit of development of current techniques is estimated at about 15 km (Patterson et al., 1973). For the purpose of estimating the geothermal resource base, it seems reasonable to regard 10 km as the maximum practical depth. It has been estimated that within this depth range, the amount of heat contained beneath each square kilometre of the earth's crust is of the order of 10^{18}J (Garnish 1976 a). This is equivalent to the heat content of 37 million tonnes of coal, or rather more than 10% of Britain's present total annual energy requirement. On the same argument, the total heat content of the crust under Britain is equivalent to 8.5 x 10^6 million tonnes of coal, enough to supply Britain's energy needs at present rates for 20,000 years. It is, or almost certainly will be by the turn of the century, <u>technically</u> possible to exploit a considerable fraction of this resource, perhaps 10% or more, although the grade of heat obtained (ie temperature) will be relatively low ($<150^oC$) in most cases. The factor which will control the extent of development in practice, however, is the <u>cost</u> of heat at the point of use, and this will be controlled in turn by three main factors:

i) the cost of deep drilling and any extraction equipment required;

ii) the cost of transmitting the heat obtained (usually in the form of steam or hot water) from the well-head to the point of use;

iii) the cost of upgrading the heat (if necessary and practicable) to a quality high enough for the application envisaged.

Finally, once certain sources have been identified as economic for geothermal development, ie heat of the appropriate grade can be obtained and transported at costs lower than those of competing sources of energy in the same location, the <u>rate</u> at which these developments can be brought into use will depend on the availability of the specialist equipment such as drilling rigs which would be required.

Consideration of all these factors has led to an estimate, which can only be tentative at this stage as much more detailed information is required, that geothermal energy might be able to supply 1% of Britain's energy needs by the end of the century and perhaps up to 10% in the longer term (Dawson 1976).

The factors listed above are interactive and cannot be considered completely in isolation when deciding on the viability of a particular development. For example, in those more favourably situated countries where geothermal energy has already been developed the preferred use has been for electricity generation, because electricity is easier and cheaper to distribute than steam or hot water and it can be used in a greater variety of markets. If 'hot rock' technology is successfully demonstrated, the possibility will exist of varying the output temperature by the choice of bore-hole depth; higher output temperatures allow cheaper and more efficient generation of electricity, but greater capital investment is needed for the deeper wells required. In the case of hot water sources, depths and temperatures are usually fixed but other choices are open to the operator, eg to generate electricity at low efficiency (using high capital cost binary-cycle or total-flow plant (Anderson 1973, Austin 1975)) but thereby create a high grade energy source which can be transmitted over long distances and used in a variety of applications, or to supply the heat as hot water directly. In the UK, it is unlikely that many geothermal water sources will prove to have temperatures exceeding 120^oC and transmission distances are likely to be limited by cost to about 10 km. For lower temperatures still, the option may arise of developing a market for heat at the geothermal site (eg by building greenhouses for horticulture) or of transmitting over a limited distance to a market which can use this low grade heat (eg a district heating scheme) or of up-grading with a heat pump to permit both a greater radius of economic distribution and a larger choice of markets. Heat pumps designed to operate in the temperature range 100-130^oC are likely to be developed in the near future.

It is evident, then, that there can be no simple answer to the question of whether geothermal sources can be economic in the UK, and each case will have to be considered on its merits. In view of the present lack of data relevant to possible geothermal sources beneath Britain, all that can be said at present is that it seems to be worth examining certain possibilities in greater detail.

It was mentioned earlier that the potential geothermal resources of the UK may be classified as aquifer sources or as 'hot dry rock', though of course the dividing line between aquifers (or at least strata containing water) of poor permeability and dry rock possessing some natural permeability is somewhat blurred.

The aquifer sources that will be of interest are those where the water-bearing rock occurs at depths great enough for the temperature to be usable but still possesses sufficient permeability to allow the heated water to be withdrawn at an economic rate without too great a requirement for pumping power. Again, the questions of "usable temperature" and "economic rate" are interactive and will vary from one locality to another, but some general observations may be made. In theory, a temperature of about 40°C could be adequate for applications such as greenhouse heating or for upgrading with a heat pump, but it would probably not be economic to extract, pump, and dispose of the very large volumes of water required for the supply of significant quantities of heat. Experience in other countries, notably France and Hungary, seems to suggest that the minimum practical temperature for an exploitable geothermal aquifer is in the range 55°-70°C. On present evidence, geothermal gradients in those parts of Britain which are likely to possess deep water-bearing strata rarely exceed 30°C/km, so that the well depths required would be 2 km or more.

At temperatures up to 100°C, the most likely market for heat seems to be domestic and industrial space heating, which on the scale of a geothermal development implies a district heating project. Since it is unlikely to be economic to transmit the hot water over distances much in excess of 10 km, this means that the geothermal site would have to be close to a centre of population large enough to use such a scheme. As it happens, two of the areas of possible interest, the Bath/Bristol region and the Midland Valley of Scotland, both possess large conurbations though at present the third area, the western end of the Hampshire basin, is relatively thinly populated. If water could be found and extracted from depths of 5-6 km, implying temperatures in the region of 150°C, then the possibility exists of using the heat in certain industrial processes such as in the food processing or textile industries, but on present evidence it seems unlikely that any aquifer located would possess sufficient permeability at these depths to allow adequate flow rates without excessive pumping. Bearing in mind that Britain uses large quantities of low grade heat (below 100°C) for space heating, it seems that the most appropriate use for heat from aquifers in the UK would be for some form of district heating, and geological interest would be focussed on the possibility of locating permeable water-bearing strata at depths of 3-4 km in regions which contain large centres of population. Recent very simplified calculations by the author suggest that a depth of 4 km is also close to the economic optimum for extraction of heat from an aquifer in a region of 'normal' geothermal gradient (25-30°C/km) (Garnish 1976 a).

Even if a suitable aquifer is located in one of the regions mentioned, a number of problems will still have to be solved. Not the least of these is that, in general, the British pattern of housing development is unsuited to large-scale district heating schemes which, because of the high costs of local heat distribution, can only be operated economically in areas of high-density housing. From the technical point of view, the aquifer will have to be sufficiently permeable to support flow rates of several tens of litres per second; almost certainly, pumping will

be required to achieve flows of this magnitude and the economics of the operation may well be controlled by the amount of power needed. In addition, waters from deep aquifers invariably contain significant quantities of dissolved solids which can cause problems in both the use and subsequent disposal of the water. Dissolved salts, which may be present in quantities of 1% or more, can lead to corrosion problems unless the correct choice of materials has been made for surface equipment such as pipes and heat exchangers. Other solids such as silica, whose solubility in water is strongly temperature dependent, can be deposited in pipes and on heat exchange surfaces, thereby reducing the efficiency of heat transfer and generally causing operational difficulties. After use, the cooler water (which still retains much of its impurity content in solution) must be disposed of. For reasons of both thermal and chemical pollution of the environment, it is most unlikely that the quantities of waste water involved could be discharged to surface drainage systems such as rivers and techniques of reinjection into the aquifer are now being pioneered in several countries. This in itself can give rise to difficulties and certainly incurs the cost of drilling additional wells.

It might seem from this that the problems of using thermal waters for space heating are so great that practical applications are ruled out. None of the problems are insuperable, however, and calculations suggest that it should still be possible to provide low-grade heat to a district heating or similar scheme at costs that are comparable with or lower than those for heat obtained from imported oil. These conclusions receive some support from the apparently successful commercial operation of geothermally-based district heating schemes in the Paris basin. At present, some 10,000 dwellings are heated by water from the Dogger aquifer at temperatures between 60° and 70°C, and plans are in hand for other installations all over France to serve nearly half a million dwellings by 1985 (Gerard, 1976; Olivet, 1976; see also footnote*). The Paris basin is part of the same geological unit as the Hampshire basin and there seems little reason to suppose that such an operation could not be carried out in Britain.

The fact remains, however, that the number of suitable sites for such developments in Britain is limited, and there seems to be little chance of obtaining significant quantities of heat at temperatures above about 120°C. If, on the other hand, techniques become available that will allow exploitation of the heat contained in dry impermeable rock then the prospects for geothermal energy to become a significant contributor to Britain's energy needs would be greatly enhanced. The fundamental problem is that rock is a very poor conductor of heat; to extract heat efficiently and economically from a mass of rock requires that a heat transfer medium be circulated over very large surface areas of the rock, arranged so that the conduction path from any point in the rock to the nearest heat-transfer surface is as short as possible. In a porous rock such as sandstone this

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*The French work was described in detail at the June 1976 meeting in Paris of the NATO/CCMS "Non-Electric Uses of Geothermal Energy" project, and a number of booklets are available from the Délégation Générale à la Recherche Scientifique et Technique (DGRST), 35 rue Saint-Dominique, 75007 Paris.

condition occurs naturally and water circulated through the permeable layer can readily extract heat from the mass of the rock. This is not the case for the great majority of the rocks of the earth's crust, however. The deeper (and therefore hotter) sedimentary rocks have been compacted by the weight of material above them, and their permeability reduced accordingly. Granites, which are usually hotter than the surrounding rock at the same depth because of their higher content of heat-producing radio-elements and which therefore offer the prospect of obtaining more heat for the same depth of borehole, are usually highly impermeable and natural water circulation is restricted to a few randomly orientated cracks and fissures. If geothermal energy is ever to make a significant contribution to the energy supply in those parts of the world that are remote from active plate boundaries, and in particular if it is ever to contribute on a scale which remotely approaches that suggested in the opening paragraphs of this paper, then this 'hot dry rock' problem must be solved.

The obvious method of producing a large heat transfer surface within a rock mass is to fracture it in some way, and a number of approaches have been investigated. Several studies have been carried out, particularly in the US and USSR, of the use of underground nuclear explosions, and it appears that such an operation would be technically feasible (Burnham and Stewart, 1973). The major difficulty appears to be the seismic effects associated with an explosion powerful enough to produce an adequate volume of shattered rock (Sandquist and Whan, 1973). These would restrict the practical application of the technique to regions remote from large centres of population and therefore, in general, remote from centres of energy demand. This objection, which applies equally to the use of large conventional explosives, would almost certainly rule out such a development in Europe.

In 1971 a group at Los Alamos Scientific Laboratory, New Mexico, proposed an apparently more acceptable solution to the hot dry rock problem (Robinson et al, 1971). They suggested that a crack of suitable surface area could be produced in an impermeable rock such as granite by hydrofracturing, and a large-scale test of this proposal is now underway at the Laboratory. Hydrofracturing of sedimentary rocks has been used for some time by the oil industry as a means of improving the productivity of oil-bearing formations and in its simplest form consists of pumping water into a well until the rock at the base of the well fractures under the combined effect of the hydrostatic head and the applied pressure. At depths greater than about 1 km in most geological environments the fracture takes the form of a thin vertically-oriented disc, the radius of which is controlled by the applied pressure and which may extend for hundreds of metres. The Los Alamos team have now demonstrated, possibly for the first time, that hydrofractures can be initiated and controlled in hard igneous rocks such as granite and it is expected that the main test facility will be in operation within the next few years (Murphy et al, 1976).

The Los Alamos experiment is illustrated schematically in Fig. 1. The test site is on the rim of a volcanic caldera in the Jemez mountains, about 15 miles from the laboratory. After penetrating 600 m of sedimentary and volcanic deposits in which the geothermal gradient is approximately 100°C/km, the bore-holes pass into pre-Cambrian granites with temperature gradients of 50-60°C/km. The plan is to sink one bore-hole to a depth of 3.8 km (where the temperature is expected to be approximately 250°C), create a large fracture at the base of this hole, and then intersect the crack with another shallower borehole. Water would then be pumped round the loop thus formed, passing down the deeper bore-hole and rising under the influence of buoyancy forces through the crack and up to the second hole. With correct choice of operating parameters, it appears probable that a good circulation pattern can be established over the crack surface so that heat is extracted uniformly from the maximum volume of rock. The water in this test loop would be pressurised to avoid steam formation, and the heat would be extracted via a heat exchanger at the surface. The test facility illustrated is expected to produce a thermal output of approximately 100 MW(th).

The present position at Los Alamos is that the first borehole has reached a depth of 2.9 km, where the temperature is about 195°C. A trial hydrofracture has been formed at this level, and intersected with a second, smaller, borehole. The connection at the moment is poor, however, and the completed circuit shows a high resistance to flow. A considerable amount of effort is being devoted to understanding the behaviour of the crack systems and the conditions governing flow resistance. Once this is achieved, it is planned to seal off this system, deepen the hole to 3.8 km and establish the main loop. Operation of the loop will be monitored for several years, in order to answer the following key questions:

- will the crack remain open sufficiently to ensure adequate circulation rates at the pressures envisaged (100-125 kg cm^{-2})?

- how will the system be affected by the chemical reactions that are likely to occur at these temperatures and pressures between the rock surface and the water?

- and, most important of all, how will the power output of the system vary as a funtion of time?

The significance of this latter question is that calculations suggest that the original crack surface will cool relatively rapidly and power output could be declining quite sharply within one year of the start of operation. It is predicted, however, that as the original crack surface cools, thermal contraction of the rock will lead to fresh cracks forming at right angles to the original surface, thus extending the zone of water circulation and heat-exchange into fresh volumes of hot rock. If this mechanism does indeed operate, and it seems that the viability of the system will depend on such an effect occurring, then the early decline in power output should be reversed and power should increase steadily over the remaining life of the system (Smith et al, 1973). It will take several years, therefore, to test all the aspects of this particular design but the outcome is awaited with considerable interest by a number of countries and, if all goes well, it is probable that several similar projects will be initiated in different parts of the world.

Among the countries watching progress at Los Alamos is Britain, and here the interest in the first instance would be in the possible application of the process to the granites of Devon and Cornwall. The present evidence, based on measurements at a few sites and at a maximum depth of only 700 m, shows that temperature gradients in the region may be around 40°C/km (Tammemagi and Wheildon, 1974). If these gradients continue to depths of 7 or 8 km (that is, if the anomalously high heat flows do not prove to be caused by the circulation of warm water at intermediate depths) then the application of a process such as that described could permit the extraction of significant quantities of heat at temperatures above 200°C. Clearly, it would be necessary to establish the existence of suitable markets in the vicinity of any development but the higher temperature of the output offers more flexibility, both in terms of the nature of the market (electricity generation, process heating, etc.) and of the economic radius of distribution. There are far too many unknowns at this stage to make any firm estimate of the economics of possible hot rock developments, but it may be noted that (perhaps surprisingly) hydrofracturing is a relatively cheap process costing only a few percent of the cost of a deep well and established technology is available for most of the other components of the system. The overall economics of the process will be determined by the long-term behaviour of the crack surface and the amount of pumping power needed to keep the crack open and maintain adequate flow rates.

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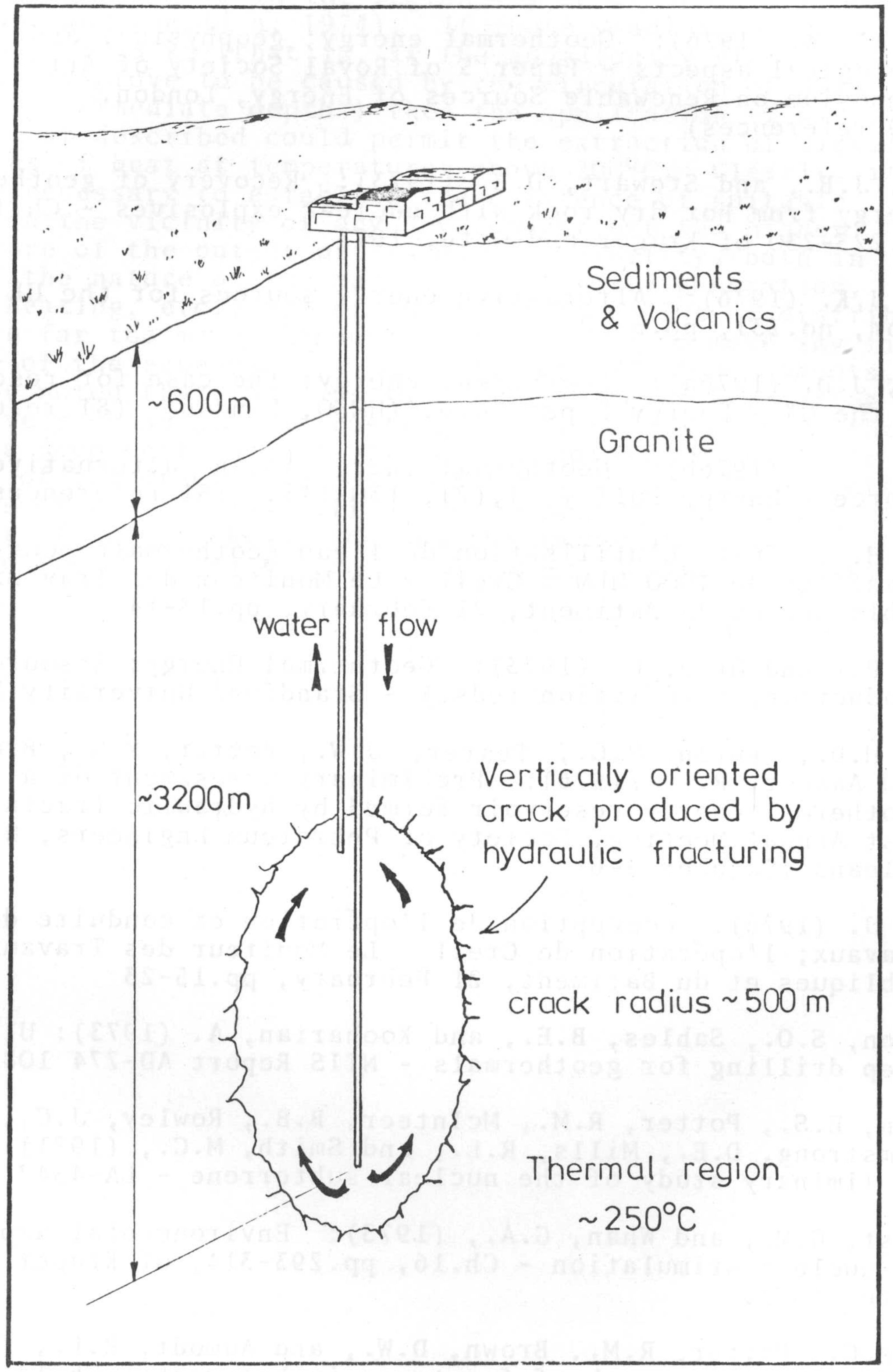

FIG.1 SCHEMATIC DIAGRAM OF LOS ALAMOS "HOT ROCK" PILOT EXPERIMENT

ENERGY FROM THE WIND

P. J. Musgrove

There is no doubt that, in suitable localities, windmills can provide locally useful amounts of power. They have done this for many centuries. However do windmills really have the potential to make a significant contribution to national energy requirements in the U.K? And if the answer to this is yes, is there any real prospect that the cost of wind generated electricity will be able to compete with electricity generated from fossil or nuclear fuels?

First let us attempt to assess the amount of power/energy in the wind. Wind data for many U.K. locations is contained in reference 1. If one plots the velocity/duration curve in the form (V/V_{mean}) versus time, as is done in figure 1, one notes that the resulting curve is virtually independent of the actual mean wind speed. One may also note, in passing, that wind speeds greater than $2\frac{1}{2}$ times the mean wind speed occur for only a very small proportion of the year - almost all the wind energy is contained in wind speeds below this. The power in the wind is proportional to the cube of the wind speed and it may readily be shown, by cubing and averaging the ordinates of figure 1, that the average power in the wind corresponds to the power in a wind speed equal to $1.34V_{mean}$. For a locality such as the Western Isles of Scotland, where the sea-level mean wind speed is about 7.2 m/s, this gives an annual average power flux of 560 W/m^2.

Recent detailed design studies in the U.S.A. for large conventional windmills, see references 2 and 3, indicate that the minimum cost, per unit of wind generated energy, corresponds to a rated power output of several Megawatts and a diameter of about 60m. Windmills such as these would intercept the power in the wind up to a height of at least 60m, and in a locality where V_{mean} = 7.2 m/s this gives an average power flux of 33.6kW per linear metre. It is interesting to compare this with the corresponding figures for the power in the waves, quoted by Salter in reference 4. At Seven Stones, just off Land's End, the annual average power in the waves is stated to be 26kW/m. At MV Famita, 300km off the East coast of Scotland, the annual average wave power flux is 37kW/m and at Station India, 700km to the west of the Hebrides, the annual average wave power flux is 77kW/m.

However, as Denton et al point out in reference 5, the cost of laying submarine cables much more than 100km offshore becomes prohibitive, so the high power flux at Station India is of academic interest only. These simple calculations indicate clearly that the power in the wind is at least comparable with the power in the waves - a fact not widely appreciated.

A hypothetical linear array of windmills would intercept an annual average power flux of 340MW along a 10km front, similar to that projected for wave power systems. However wave power systems are of necessity limited to one - dimensional arrays; wind energy systems can be deployed in two-dimensions. A line of windmills will produce a wake of reduced wind velocity which extends downwind a distance that is approximately ten times the height of the windmills. Beyond this distance the wind speed recovers, through shear and mixing with the air above the windmill height, to its original velocity. A second line of windmills can therefore be placed some 600m downwind of the first, and will intercept a further 340MW. If one assumes, more conservatively, a separation of 1km between successive lines of windmills, then the average wind power flux intercepted by 10 lines of windmills, each 10km long, arranged in a 10km square, totals 3400MW. The overall efficiency of a good modern windmill is typically about 33%, so windmills deployed within this 10km square could provide an annual average power output of about 1000MW (=1GW). Since the annual average demand for electricity, within the area served by the CEGB, is approximately 25GW this would represent 4% of our total electricity requirements.

In practice, of course, one would not deploy windmills in simple linear arrays, otherwise there would be an excessive loss of power when the wind direction was parallel to the lines. To avoid this windmills would be deployed over a given area in a pattern that would take account of the distribution of directions from which the wind could be expected. The optimum arrangement of such arrays has been studied in Sweden, as part of their National Wind Energy Research Programme, and Ljungstrom indicates some preliminary conclusions in reference 6.

Where, in the U.K., might such arrays of windmills be located? The

Western Isles provide one possible locality, where annual mean wind speeds exceed 7 m/s, but this location is remote from the main centres of population and energy use, and there would undoubtedly be aesthetic objections to siting large number of windmills in such a remote and unspoilt area. My preference is to deploy windmills in the shallow waters of the southern North Sea. To the east and south of Hull the area of the southern North Sea within British jurisdiction is approximately 40,000 square kilometres. This region is close to the main centres of population and energy use, and Meteorological Office data indicates that it has an annual mean wind speed of about 7.3 m/s. Moreover for much of this area the water depth is less than 20m, see reference 7. Windmills deployed in clusters over just 2%* of the southern North Sea could provide more than 20% of our total electricity requirements; pro rata for larger areas, and this area is not the only suitable windy and shallow location around our coasts.

Windmills deployed in shallow offshore regions therefore do have the potential to supply a very significant part of our total electricity requirements. If the proportion of wind generated electricity is only a few percent of the total, wind energy systems may be integrated into the grid system without too much difficulty, and used as fuel savers. However, if we decide to supply a large percentage of our electricity from the wind, it is imperative that the wind energy system be combined with a large capacity energy storage system, so as to provide power on windless days. At the present time the most attractive method of energy storage would appear to be compressed air, stored underground. Glendenning, in reference 8, indicates that the cost of such an energy storage system is typically about £100/kW, and this cost is dominated by the surface equipment, i.e. the compressors and turbines. Such a system is well suited for use in conjunction with wind energy systems in the southern North Sea, since this

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* Since $100km^2$ could give an average of 1GW, $800km^2$ could give 8GW, i.e. 32% of our average electricity requirements. However since space in the southern North Sea is not at a premium, a larger separation between windmills would probably be preferred.

area contains most of our natural gas fields, which are now being rapidly depleted. The strata from which this gas comes will provide a large and very suitable storage reservoir for compressed air. Surplus wind energy on windy days would then be used to compress air, which would be stored in these strata until the energy is required on windless days.

When air is compressed most of the input energy appears in the form of heat. It is essential therefore that heat losses from the storage system be minimised. Fortuitously the natural gas bearing strata under the North Sea are relatively hot, about 120°C, as this is geothermally one of the best areas within the U.K. If the compression ratio is arranged so that the compressed air is pumped down at this temperature, heat losses will consequently be negligible.

Windmills deployed over a small part of the southern North Sea can, in conjunction with underground compressed air storage, provide power on demand and so substitute for nuclear or fossil fuelled power stations. This will only be worthwhile if the cost of wind generated energy is comparable with the cost of energy derivedfrom fossil or nuclear fuels. It is notoriously difficult to predict the costs of any large, new engineering system - it is difficult enough even to predict the future costs of existing systems. However most of the components of an offshore wind energy system are sufficiently well defined to permit a crude estimate of its overall cost. For the basic windmills, recent American studies, e.g. reference 2, indicate a production cost of about $450/kW (£280/kW) for megawatt rated units of conventional design. Figure 2 is typical of such recent designs, and a 1.5MW unit similar to this will be constructed in the U.S.A. within the next two years. Deploying such windmills offshore will add to the cost, though preliminary studies indicate that in shallow waters this extra cost will not be prohibitive - my guesstimated figure is an extra £100/kW. To this one must add the cost of the energy storage system, at £100/kW, and the cost of the submarine transmission of power to the mainland. Typically the distance from the windmill array to the shore will be about 50km. Denton et al (reference 5) indicate a cost of £0.5 per megawatt metre for submarine power transmission, so this gives an additional cost of £25/kW. The total, for an offshore wind energy system with energy storage,

is therefore £505/kW. It should be noted that the windmill cost of £280/kW is for a design which has a plant factor of 51%, but the extra cost of providing a higher plant factor (or extra rated capacity) can be largely offset by the reduction in cost which the development of vertical axis windmills is expected to provide. Figure 3 shows the prototype of the variable geometry vertical axis windmill developed at Reading and now patented worldwide by the N.R.D.C.

To put in perspective the estimated cost of £505/kW, for the offshore wind energy system, it may be noted that the 2.4GW nuclear power plant ordered in New York State in July 1976 cost $3.2 billion, i.e. $1333/kW or £830/kW. It would be imprudent at this stage to claim that wind energy systems will be cheaper than nuclear power stations, but the projected costs of wind energy systems certainly appear to be competitive. And it does seem possible that North Sea Wind may join North Sea Gas and North Sea Oil in making a very useful contribution to our energy requirements; with the difference that North Sea Wind will continue to be available to succeeding generations. What is needed now is a national wind energy research and development programme, so that the potential of wind energy may be realised as speedily as possible.

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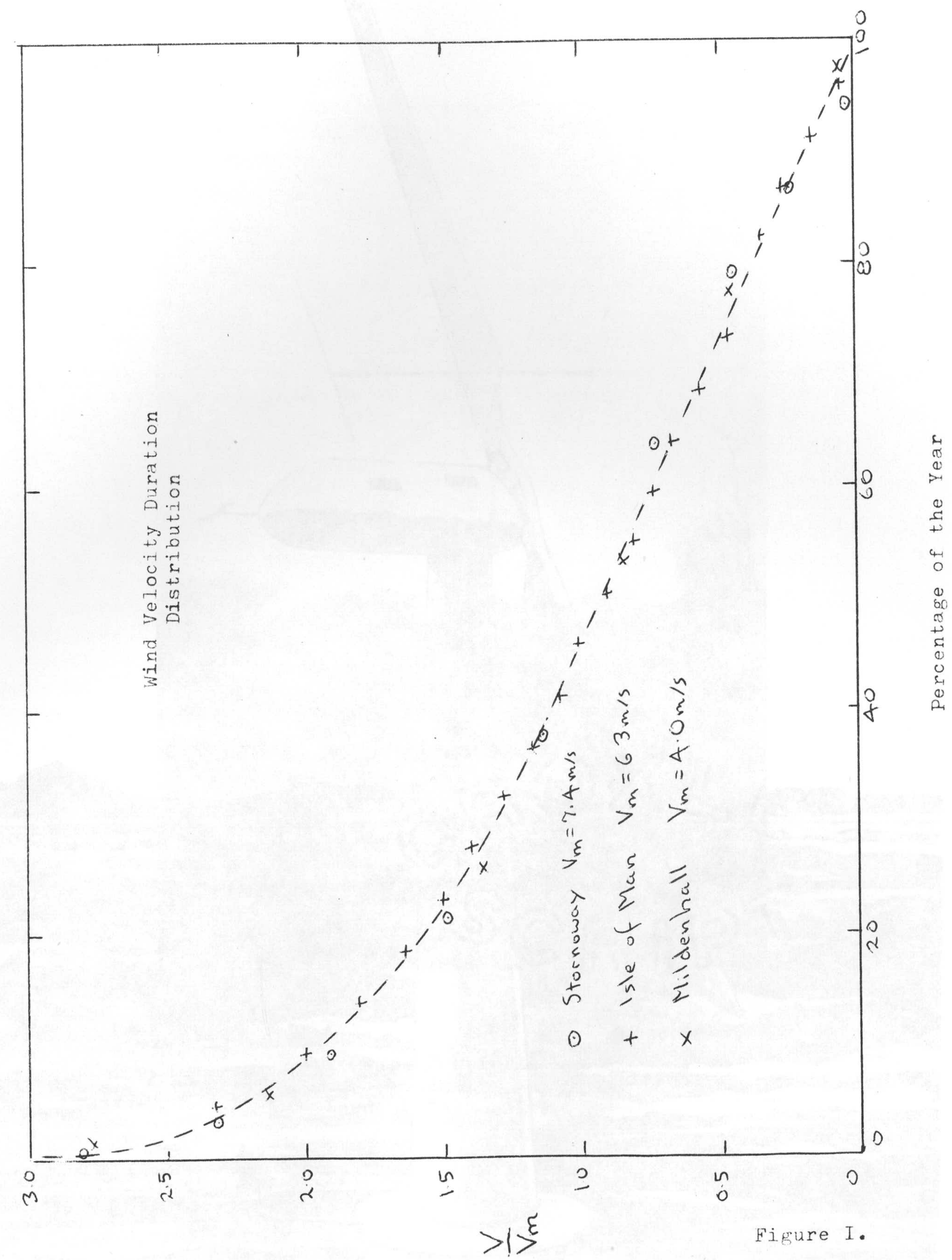
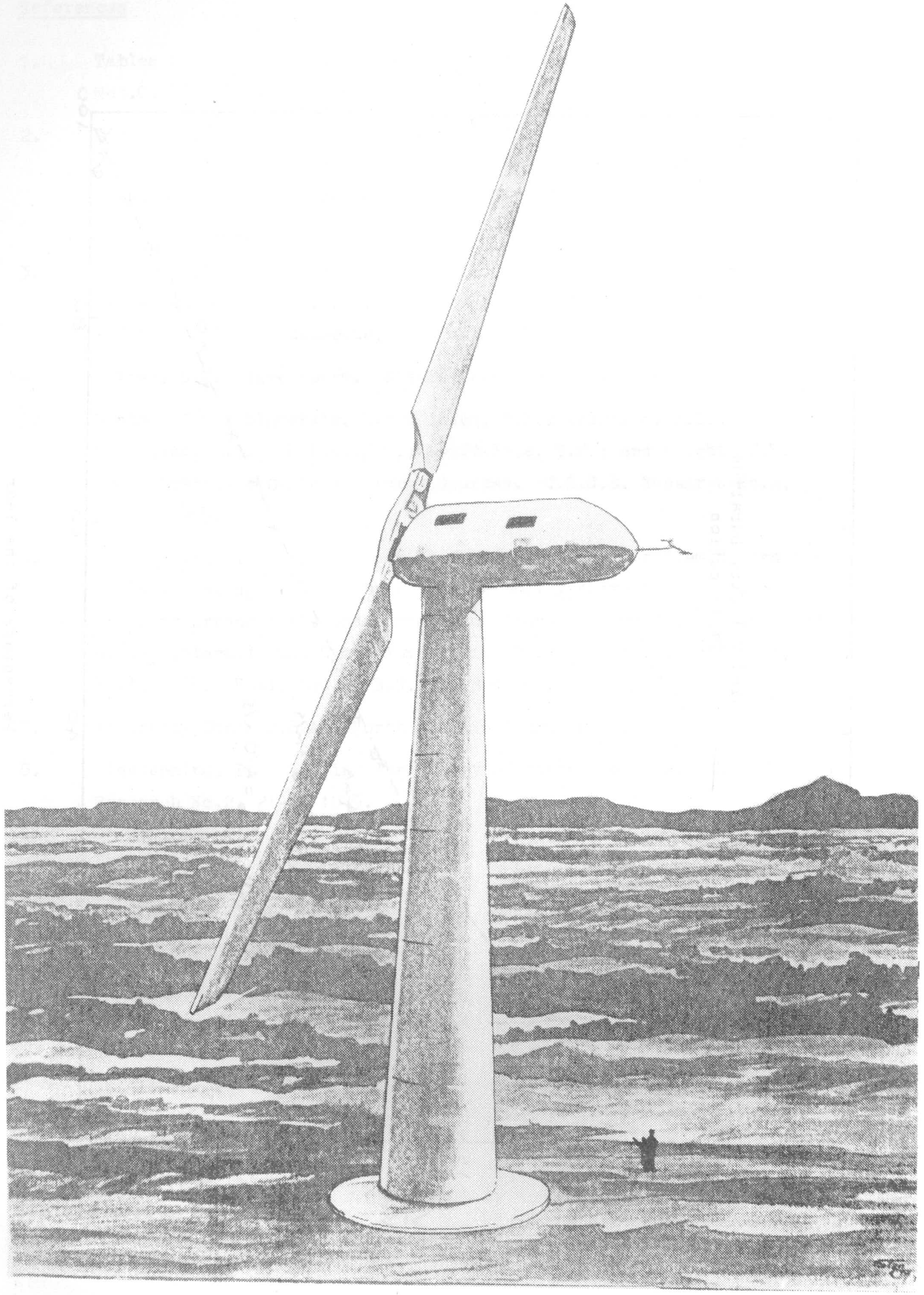


Figure I.



Kaman 1.5 MW Design

Figure 2

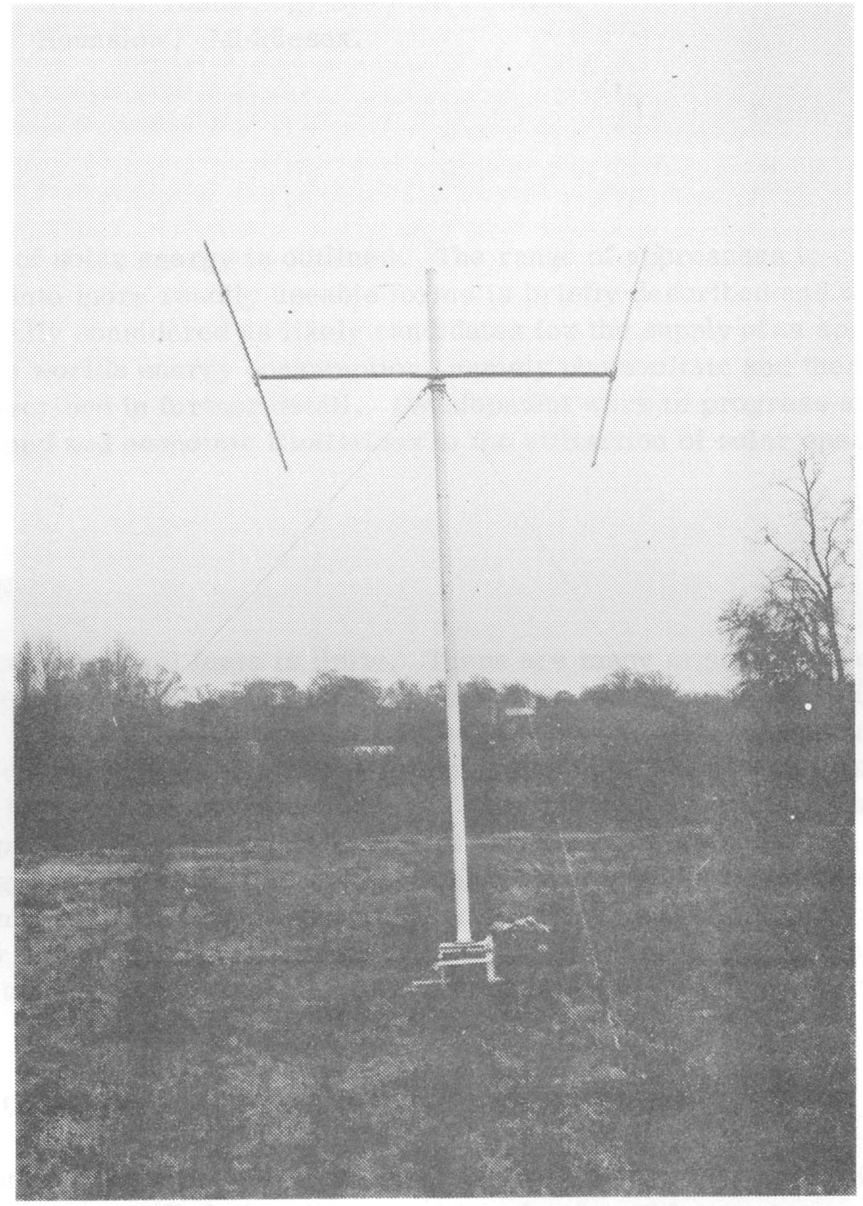


Figure 3

Prototype Vertical Axis
Windmill
Reading University

SOLAR ENERGY - THE POWER AVAILABLE AND THE PRACTICAL LIMITATIONS

Bernard McNelis
General Technology Systems Limited.
Hounslow, Middlesex.

SUMMARY

The availability of solar energy is outlined. The range of approaches to conversion of solar energy into more readily useable forms is briefly described and those systems which are currently considered as likely candidates for the supply of an appreciable proportion of the worlds energy consumption, namely photovoltaic and thermal conversion, are described in further detail. Development work in progress around the world is mentioned and economic limitations to the utilisation of solar energy are listed.

INTRODUCTION

The Earth's supply of fossil fuels is finite. There are many arguments about the exact date by which the supply will be totally depleted, but this date is within the forseeable future. Nuclear fission could supply our needs, but there are technical and also serious environmental problems. Nuclear fusion is very attractive as an energy supply but it is as yet an unproven technology. It is therefore essential that steps are taken to expand research, and development in the field of, so called, 'unconventional' energy sources, and also create an appropriate environment in which applications can expand. Of these energy sources, solar, as the primary and most abundant supply of energy, offers immediate utilisation in low temperature applications, and potential economic application in very large scale power production.

ENERGY CONSUMPTION AND THE AVAILABILITY OF SOLAR ENERGY

The consumption of energy by individual countries such as the UK, and by the Earth as a whole has been quantified elsewhere, and trends of world energy consumption have been assessed and predicted by, for example, the Institute of Fuel. (1) The relationship between energy consumption and solar energy availability has been indicated by many authors in different ways, and repeating some of these, so as to give perspective to the immense amount of primary energy which could be exploited, it can be stated that the present world energy consumption is less than the solar energy intercepted by a region 100 km square in a favourable location. Considering the UK, a conversion device with an efficiency of 10% would require 7.8% of the UK land area to supply all our energy demand (1973 level) while to supply only our electricity demand from the same device would require 0.96% of the land area.(2)
In comparing the availability of solar energy with the world's known fossil fuel reserves, one can conclude that the total fossil fuel supply has a chemical energy content equivalent to the solar energy intercepted by the earth in less than two weeks.

Outside the Earth's atmosphere the solar energy flux is almost constant at about 1.35 kW m^{-2}, but absorption and scattering processes in the atmosphere reduce this flux to a maximum of about 1.0 kW m^{-2} at sea level. The total amount of solar energy available in a year at a given location depends on a latitude and local climatic conditions. Solar intensity is diminished at high latitudes because of the longer path through the atmosphere and hence more absorption and scattering, and at higher latitudes there is a pronounced variation between summer and winter energy availability.

Solar energy input (horizontal surface) to the inhabited part of the earth varies from about 700 kWh m^{-2} year $^{-1}$ in some parts of Northern Europe to about 2300 kWh m^{-2} year $^{-1}$ in some desert regions of the USA. The average for southern England[3] is about 890 kWh m^{-2} year $^{-1}$ and this varies during the year from about 0.4 kWh m^{-2} day $^{-1}$ in December to 4.5 kWh m^{-2} day $^{-1}$ in June. This seasonal variation, and also the fact that there can be many consecutive days where there is virtually no insolation, are possibly the greatest problems to successful exploitation of the solar resource rather than the net annual energy available.

COLLECTION AND CONVERSION OF SOLAR ENERGY

The solar energy which reaches the Earth's surface is partly reflected and partly absorbed causing a heating effect on the surface which in turn gives rise to longer wavelength re-radiation. This is in effect a constant energy flow and fixes the equilibrium temperature of the Earth. Some of this energy flow can be tapped and re-routed so as to do work before being dissipated as heat and re-radiated to space. An indication of the range of ways in which solar energy can be converted to more useable energy forms, such as fuel, electricity, and heat is given in figure 1.

Solar energy is already collected and stored on a vast scale by photosynthesis, yet only about 0.02% of the incoming solar radiation is fixed in this way. There is considerable scope for greater energy production through photosynthesis[4] and the production of biomass for fuel is currently being studied in Ireland [5]. Photochemical conversion also offers promise both as a means of producing electricity via a photogalvanic cell (regenerative fuel cell) or by direct conversion to storeable fuel [6]. It is not possible to deal with these aspects in further detail here.

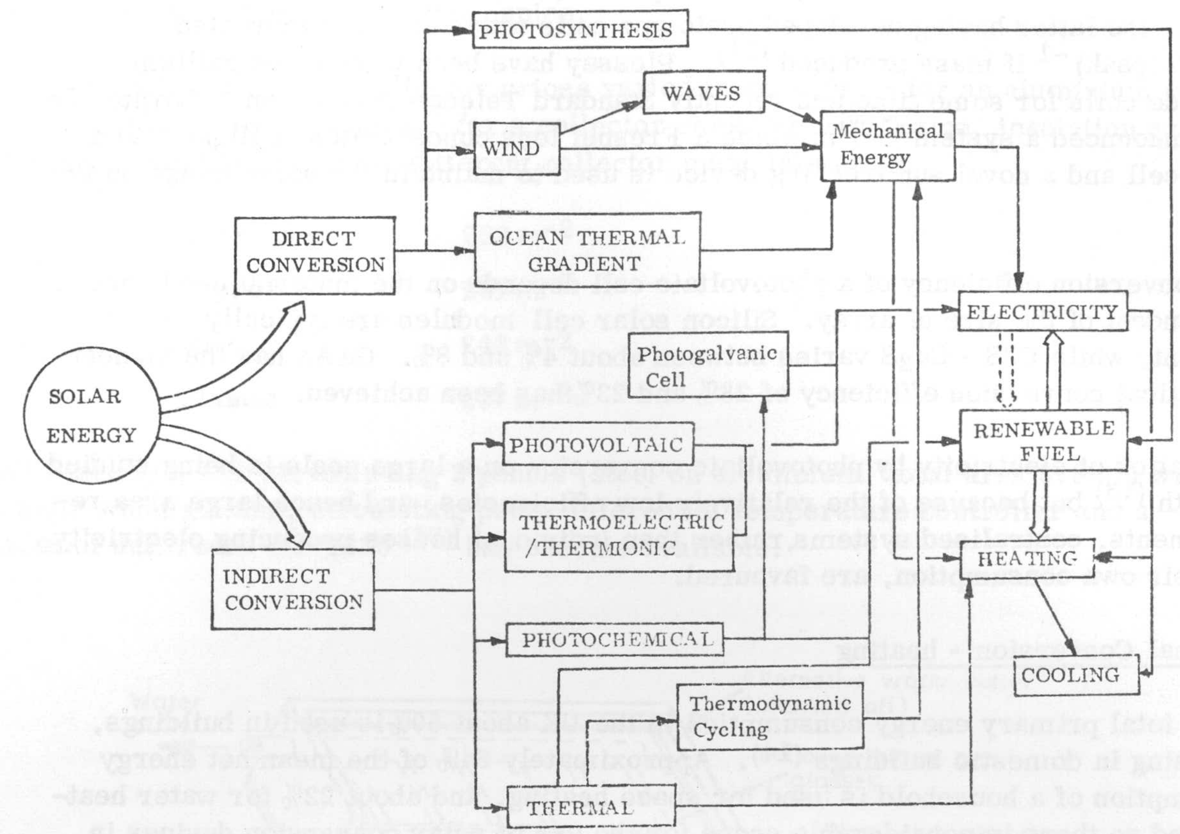


FIG.1 ALTERNATIVE CONVERSION PATHS FOR SOLAR ENERGY

Photovoltaic Conversion

A photovoltaic, or solar, cell converts sunlight directly into electricity [7] and this has been developed into very pratical devices of proven reliability. Solar cells are used extensively in spacecraft and, encapsulated in suitable modules, they are finding a rapidly growing application as a source of small amounts of electricity in remote places. Currently the only commercially available terrestrial modules are based on silicon solar cells and these are manufactured in the UK by Ferranti and similar products imported from the USA are marketed by Lucas and Solarpak Products. All of these cost about \$20 W(peak) $^{-1}$. At this price level the only market is in places without mains electricity supply, but this can be a considerable size, for example, in developing countries [8]. Major R & D efforts are underway to reduce costs of solar cells and the US programme has as one of its milestones, the development of cells costing \$0.40 W(peak) $^{-1}$ by 1985 [9] and cost predictions have been further evaluated in detail [10]. In the UK work is underway on development of ribbon silicon for solar cells at Metals Research, and also on cadmium sulphide - cuprous sulphide thin film cells at International Research and Development (IRD), G.V. Plannar, and PATS Centre, the latter having developed prototype cells which could be marketed at $0.20 W(peak)$^{-1}$ if mass produced [11]. Plessey have been working on gallium arsenide cells for some time and recently Standard Telecommunication Laboratories have announced a system [12] in which a Fresnel lens concentrates sunlight onto a GaAs cell and a novel sun tracking device is used to maintain the solar image on the cell.

The conversion efficiency of a photovoltaic cell depends on the material used, and is independent of the size of array. Silicon solar cell modules are typically 10% efficient, while CdS - Cu_2S varies between about 4% and 8%. GaAs has the highest theoretical conversion efficiency of 28% and 23% has been achieved.

Generation of electricity by photovoltaic conversion on a large scale is being studied in depth [13] but because of the relatively low efficiencies, and hence large area requirements, centralised systems, rather than individual houses producing electricity for their own consumption, are favoured.

Thermal Conversion - heating

Of the total primary energy consumption in the UK about 50% is used in buildings, 29% being in domestic buildings [14]. Approximately 64% of the mean net energy consumption of a household is used for space heating, and about 22% for water heating, and so there is considerable scope for the use of solar conversion devices in this sector.

The flat plate solar collector which converts solar radiation to thermal energy has been extensively developed. The construction of a typical collector is indicated in figure 2.

The operation of the flat plate collector is well known and is described in all the standard texts.

In the UK, because of the seasonal and daily variation in the solar energy available, solar heating devices must be considered as devices for fuel economy rather than replacements for conventional systems. This is because of the lack of availability of any viable form of long term thermal storage. Interseasonal storage systems are the subject of a number of studies, but these are not discussed here.

Flat plate collectors have been used in the UK for heating swimming pools for many years where economics are very favourable [15]. More recently their use for provision of domestic hot water has increased immensely and the number of UK manufacturing and marketing organisations providing flat plate collectors is continuously

growing. A recent survey [16] compared 28 collectors from 20 companies, and suggested that there was a total of about 30 suppliers, and more recently the author has compiled a list of 78 such companies.

The survey indicated that collector prices varied from £10m^{-2} for an aluminium roll bond absorber plate to £100m^{-2} for a collector complete with frame, insulation and glazing. Average prices for different collector materials were:

Aluminium	£52 m^{-2}
Copper	£51 m^{-2}
Steel	£48 m^{-2}
Plastic	£27 m^{-2}

and recently a DIY kit including 2 panels (steel on aluminium, total area 3.8m^2) with acrylic sheet glazing, circulating pump, differential temperature controller and a gallon of antifreeze for £225 [17] has become available.

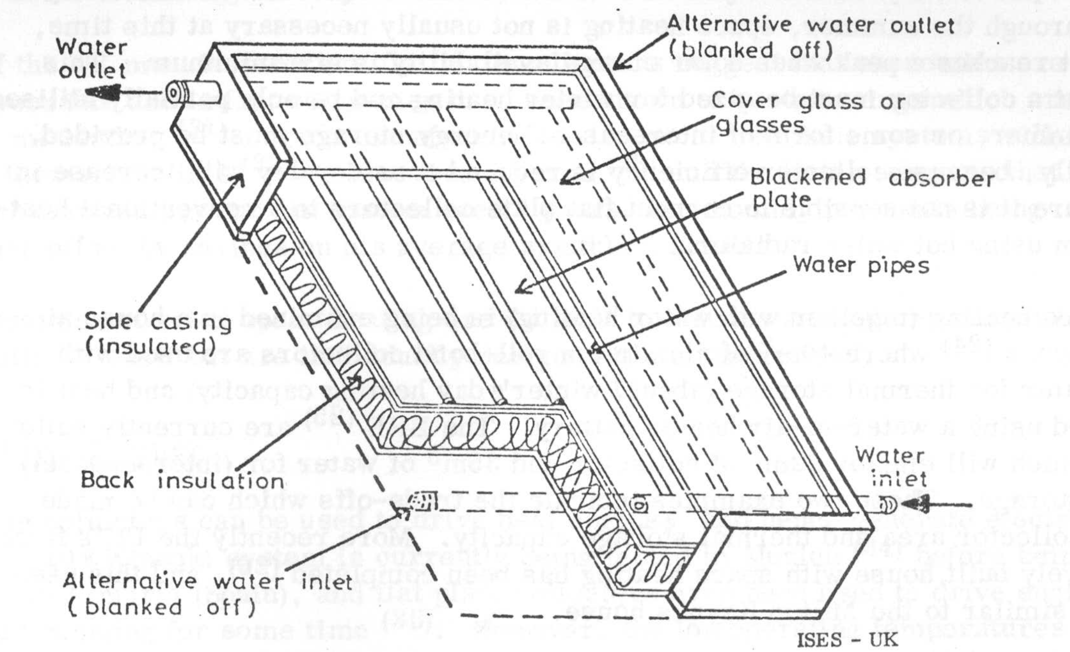


FIG. 2 FLAT PLATE SOLAR COLLECTOR (figure courtesy of ISES-UK)

Local Authorities have become interested in provision of solar water heating systems in their houses, and the South London Consortium [18,19] will be providing a $5m^2$ array on a house and are experimenting with a $1m^2$ test rig while Telford Development Corporation [20] are assessing the performance of two systems; a $4.1m^2$ aluminium collector located on the porch of a house and operating on the thermo-syphon principle and a $4.7m^2$ mild steel collector mounted on the roof of the same house.

Patterns of domestic energy use can vary widely and so the optimum size for a solar water heating installation also varies. ISES-UK [21], consider $4m^2$ suitable for an average household and suggest this would operate at an average efficiency of about 35% over the year, supplying 30 to 40% of heat required for water heating. The Building Research Establishment (BRE) [22] have calculated that this size of collector would provide about 40% of heat required or perhaps 50% in South West England. Brinkworth [23] considers that $15m^2$ would be necessary to provide most of the hot water requirements in summer and a useful fraction of it in winter.

The use of flat plate collectors for space heating has been studied in the UK, but there is considerably less activity than with water heating. Whereas domestic hot water is required all year round and so a collector installation can be effectively utilised through the summer, space heating is not usually necessary at this time, and in fact reaches a peak when solar energy availability is at a minimum. This means that a collector must be sized for winter heating and be only partially utilised during summer, or some form of interseasonal energy storage must be provided. Additionally, because collector efficiency is reduced considerably with increase in temperature it is not sensible to connect flat plate collectors to a conventional heating system using hot water radiators.

Solar space heating (together with water heating) is being examined in a house at Milton Keynes [24] where $40m^2$ of aluminium roll-bond collectors are used with $5m^3$ of water for thermal storage (about 1 winter's day heating capacity) and heat is distributed using a water-to-air heater battery. The BRE [25] are currently building a house which will employ $22m^2$ of collector and $35m^3$ of water for (interseasonal) thermal storage. These two examples indicate the trade-offs which can be made between collector area and thermal storage capacity. More recently the UK's first speculatively built house with space heating has been completed [26], and this uses a system similar to the Milton Keynes house.

Present R & D is aimed at improving collector and complete system efficiency and reducing costs. Additionally, some standardised approach to testing and performance rating of collectors is necessary. The National Bureau of Standards in the USA [27] has carried out some pioneering work and currently in the UK ISES is collaborating with British Standards [28] to reach some performance standard. The EEC Joint Research Centre at Ispra (Italy) is assessing the performance of identical collectors in different parts of Europe and in the UK the Solar Energy Unit at Cardiff and the

BRE are collaborating.

Relevant activities in Europe and other parts of the world have been reviewed by ISES [2] and in a contract for the EEC [29].

The Economics of Solar Heating

A solar hot water system with $4m^2$ of collector could be expected to save about 1500 kWh year^{-1} [21,22]. Obviously the amount of money saved depends on the fuel which is offset, but with electricity at £0.02 kWh^{-1} savings would be £30. The cost of this system would vary between about £300 using commercial collectors installed by the owner to about £600 to £700 if professionally installed, while the Telford Development Corporation simple system [20] is claimed to cost only about £150. Obviously looking at these figures the economics do not appear favourable as was concluded by Courtney [22], who using £300 as the cost of a system and electricity price of £0.019 kWh^{-1} concluded that an annual increase of 70% energy costs would be necessary to make the collector cost effective. Brunt [30] has studied the economics of collectors using figures published by ISES-UK and when considering the effect of inflation on the value of capital has concluded that this current solar technology is very close to financial viability.

Some of the UK manufacturers of flat plate collectors suggest that economics are very favourable and in fact companies have been known to quote savings which are at least misleading [31]. Some manufacturers also quote that their systems will pay for themselves in 4 [32] or less than 5 years [33] and the latter suggests that the purchaser can pay for his system over 5 years, his monthly payments being more than offset by savings on his average monthly fuel bills.

The economics of solar space heating are difficult to discuss as systems cannot be bought off-the-shelf but are individually designed and manufactured.

Solar Thermal Power

Flat plate collectors can be used to drive heat engines and hence generate electricity, and a 10 kW(peak) system is currently being tested in Munich [34] before being installed in Almaria (Spain), and flat plate collectors have been used to drive engines for water pumping for some time [35]. However, the low operating temperatures and the second law of thermodynamics means that efficiencies are not very high.

In order to increase efficiency, operating temperatures must be increased and this involves focussing solar energy onto an absorber which requires that the sun is tracked. A large proportion of the UK's insolation is diffuse and therefore cannot be focussed, and so it does not appear possible that such systems will find application here. However, these systems have been considered in this country [36] and studied in depth in the USA [37] where cost estimates of $1000 kW (installed)$^{-1}$, which is very competitive with conventional systems, have been prepared. The UK is participating in two international collaborative efforts to develop large scale solar-electric generating plant.

The EEC has supported a study of the technical feasibility and system definition of a 1 MW(el) helioelectric power plant, and is currently considering its construction as a demonstration and experimental facility. This is based on the heliostat field/central receiver concept in which a large number of identical (nominally flat) mirror systems (or heliostats) track the sun and continually reflect the incident energy into a receiver placed at the top of a tower. Super-heated steam is generated in the receiver and this drives a conventional turbine coupled to an alternator. This work has been conducted by a team drawn from Germany, France, Italy and the UK [38]. The concept is summarised in figure 3.

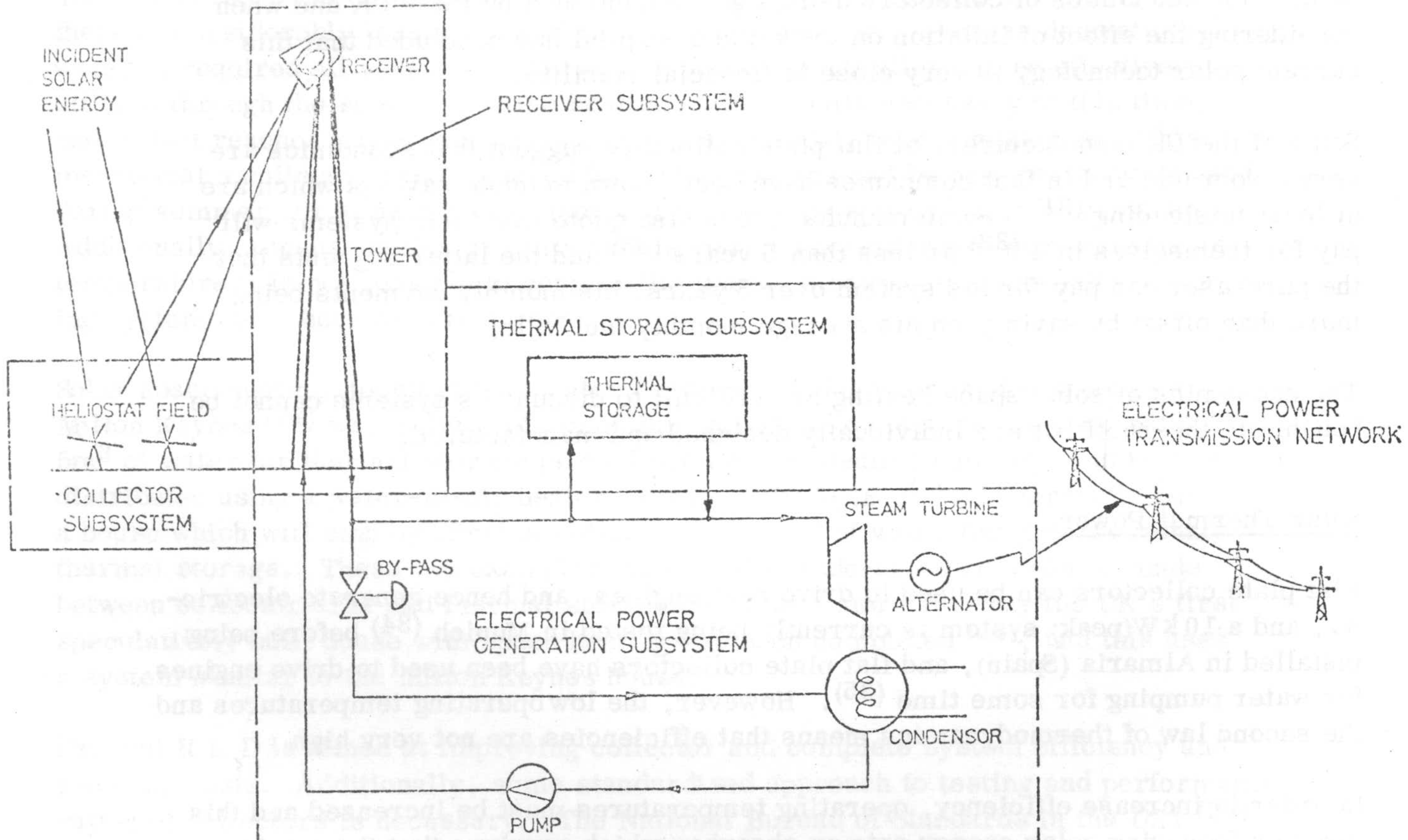


FIG. 3 CENTRAL RECEIVER/HELIOSTAT FIELD SYSTEM CONCEPT

A second power generation project has been initiated by the International Energy Agency under the leadership of Austria [39] to build a 500 kW(el) plant probably using distributed parabolic trough collectors and a conventional steam cycle/electrical system.

The economics of large scale solar thermal electricity generation systems have been examined in the USA where they are believed to be favourable and in Europe the International Institute for Applied Systems Analysis are studying these systems [40] as options for energy supply.

CONCLUSIONS

Photovoltaic cells are being used economically throughout the world to produce small amounts of electricity. R & D in progress should reduce costs considerably and lead to an expansion of the market for these devices.

The flat plate solar collector is readily available in many different forms from an ever growing number of manufacturers. Depending on how one views future rates of inflation and fuel costs, hot water can be provided economically. Solar space heating is being employed in the UK but the economics are not yet clear.

Electricity can be generated on a large scale using high temperature solar thermal systems. Published American studies indicate that economics should be attractive, but European studies in progress will lead to a better appreciation of costs involved.

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A WORLD ENERGY POLICY

M W Thring
Queen Mary College, London

1. WHY WE NEED A WORLD ENERGY POLICY

The short term 'expedient' decisions of the politicians of all countries may be compared to the situation of men lost in a forest in a thick fog. One tree looms up in front of them and they turn through a right angle to avoid it and soon walk into another. Among the examples of such short term dilemmas one can list :

1) The U.S. attempts to avoid air pollution from vehicles which led to a 20% increase in fuel consumption.
2) The dilemma of censorship and corrupting literature.
3) The dilemma of arms escalation and defence.
4) The dilemma of inflation, unemployment and bankruptcy.

It is becoming increasingly clear that this short term 'drunkards walk' is leading us to disaster. Fig.l illustrates our present situation - every one of the trees in the forest is so important that it has had a world conference about it, but it still gets more menacing. In many parts of the world the people live under the trees nearest to the edge of the precipice and we are in grave danger of falling over into one of the four disasters.

1) Famine and pestilence killing millions instead of just thousands as at present.
2) World War 3 with the unrestricted use of nuclear, chemical and biological weapons.
3) Breakdown of law and order through crime, violence, muggings, hijackings and random bombing to the point where the ordinary citizen has to go around armed and is prepared to shoot his neighbour in self defence.
4) 1984 situation in which ' big brother ' allows no one any freedom of thought, word or action, so that life has no joy in it (zero quality of life) and people don't care whether they are alive or dead.

In order to avoid civilisation falling over the precipice, we need a map of our situation showing the way out of the forest to a decent life and a compass to find a way among the trees. The compass we all have is our conscience that tells us that some actions are selfish, greedy, power seeking, destructive or steeped in hatred,while others are creative of a better world, altruistic and loving.

To establish the map we must look for the necessary conditions for a stable world with a decent life in the next century. The first facts relate to population growth. At the present there are just under 4,000 million people on the earth and the growth rate is such that unless we have world wide starvation, disease or war, the number of people will be over 7,000 million by the end of the first decade of the XXIst century. I believe that the engineers can provide the machinery, so that all these 7,000 million people can earn fully healthy & worth-while lives by doing interesting work, but that if the world's population were to double again to 14,000 million, then it is impossible to provide these conditions within the limited resources of the earth.

Now roughly 1/3 of the world's population are in the countries that have had the benefit of the industrial revolution and these countries have an annual population growth rate of about 1%. The remaining 2/3 of the world's population are in countries where almost all the people live well below an adequate standard of living and their annual population growth rate is about

3%. I think this makes it absolutely clear that the only humane way of levelling off the world's population is to give all the people of the world a decent standard of living and a decent education based on the good consequences of the first industrial revolution without the bad consequences. Moreover, if the population is to level off by the year 2010, we shall have to have substantially accomplished this Herculean task well before the year 2000, because of the ½ generation delay between the spread of voluntary family planning and a considerable reduction in the birth rate.

The first industrial revolution has had some consequences so valuable for human life that it is clear that we must have the technology to provide them for all humanity. These include : (1) Plenty of good rich food; (2) Comfortable homes; (3) Hygiene, sanitation and preventive medicine; (4) Educational possibilities for all and (5) Shorter working hours giving leisure for travel, sport. However, there have also been bad consequences which are rapidly overhauling the good ones because we have not been able to stop at the optimum point, but push on relentlessly towards the accumulation of unnecessary status symbols. These include :

1. Pollution of all kinds*, noise and ugliness, the destruction of natural beauty, trees and wildlife.
2. Arms escalation, leading to violence, muggings and fear.
3. Accidents, in home, road, factory, mine or air, largely due to cheap engineering.
4. Overcrowding, high rise flats, traffic jams, lack of exercise and other unnatural features of crowded city life.
5. The exhaustion of the most accessible resources, especially oil.
6. Destruction of job satisfaction, pride in craftsmanship and responsibility in most industrial jobs.
7. We have so far been able to absorb most of the industrial products in spite of the engineers success in increasing production per man hour by increasing the consumption of goods. If, however, we increase production by 4% p.a., it means a 50 fold increase in a century and clearly this increase in consumption per capita must hit the stops because of raw materials limitation, space limitation and increasing consumer resistance. Thus, sooner or later, the engineers efforts at automation, robotics, etc. must lead to escalating unemployment in the rich countries. Many large towns in the poorer countries have thousands of unemployed people living in dire poverty.

Now the industrial revolution is essentially based on energy. Fig.2 shows the relation between TCE and GNP for a range of countries. The energy in the food eaten by a normal healthy adult in a year is equivalent to 180 kg of coal or 0.18 TCE (tons of coal equivalent per head per year). The rich countries use an average of about 5TCE of energy for all purposes, so each person can be regarded as having about 30 slaves working for them. These countries, which contain 30% of the world's population, consume 80% of the energy, i.e. they consume

* Some aspects of pollution which are particularly worrying are the gradual build-up of lead in the water and food of humans, due to the car exhausts with leaded petrol, the effect on the trees of Norway (which has a naturally acid soil) due to the SO_2 emitted by the power stations of Britain and Western Europe and the increase in mortality in cities from bronchitis and lung cancer caused by polluted atmospheres. (Lave and Seskin, Science 1970 vol.169, p.273).CO often reaches 50 ppm in the city streets (Newell Scientific American, Jan. 1971) and is higher over the whole Northern hemisphere than the Southern because of the much greater number of cars.

about three times the world average TCE which is 1.8. The USA, with 6% of the world's population, has the world's highest energy consumption at nearly 10 TCE and uses 30% of the world's total energy. Britain, with a population of 1.6% of the world, uses 3% of the energy, 5.5 TCE and comes on the upper limit of the band of points in Fig.2, signifying that we get the least benefit for our energy, i.e. we are the most energy extravagant country. This is clearly due to habits caused by our cheap and plentiful coal of the last century.

The underdeveloped countries, on the other hand, use 20% of the energy with 70% of the population and an average of about ½ TCE, so that they average 2 slaves each and many of them have barely enough energy to produce a daily hot meal.

Now I have already concluded that we have to give all the good results of the industrial revolution to 7,000 million people in the next century. It is also certainly true that this vast gap in standard of living (and hence of TCE) between rich and poor countries, must essentially vanish if we are to avoid the tensions that lead to world war 3. Now, if we were to try to raise the TCE for all 7,000 million people to the present average in the rich countries, we should be consuming six times as much energy as we are now, and this is clearly impossible on any basis because of (i) the resources needed for the energy supply, (ii) the capital resources needed to convert the energy to useful form and (iii) problems of waste heat and pollution by combustion gases (SO_2 and CO_2) and radioactivity. The effect of thermal pollution has been studied in the USA where it has been shown (P R Ehrlich and A H Ehrlich Population Resources Environment) that the annual mean temperature in cities is 0.5 - 0.8 C higher than in the country, cloudiness 5-10% greater and fog 30-100 more prevalent. A 1000 MW power plant heats 50 m^3 of water per second by 7-14 C and this causes a reduction in the dissolved O_2 in the water, accelerated bacterial decomposition and the destruction of the larger water species. If evaporative cooling towers are used, as in Britain, a great increase in cloud and precipitation is produced. If the US consumption of electric power were to continue to double every ten years for another thirty years, the cooling demand would raise the entire annual run off of the US by 10 C.

In the Los Angeles basin, man already dissipates energy at a rate of 5.5% of the absorbed solar energy, while it has been estimated that by the year 2000, the Boston to Washington Megalopolis will contain 56 million people on 30,000 sq.km. and dissipate energy at a rate of 50% of insolation in winter and 15% in summer.

Since 1880, the CO_2 content of the atmosphere has increased by 12%. This caused a rise in temperature to the 1940's due to the greenhouse effect; since then the temperature has fallen, probably due to an increase in dust content of the atmosphere. The trails of high flying aircraft can trigger the formation of high cirrus clouds and so cause a significant loss of insolation at ground level.

We can therefore draw two inevitable conclusions as to the essential conditions for a decent world for our grandchildren :

1. The energy consumption in the rich countries will have to come down to a figure roughly around the present world average of 1.8 TCE, and that in the poor countries will have to come up to around the same figure. In this way, the total world energy consumption will only double in direct proportion to the population increase.

2. Only those energy conversion processes will exist in the next century which can be constructed to satisfy the needs of 7,000 million people within the limited capital resources of the earth (e.g. mineral ores, energy requirements for construction, cooling water, uncontaminated air supply).

In the remainder of this paper, I shall try to show how these conditions can be satisfied.

Fig.3 illustrates the kind of TCE/year relation that a British energy policy must allow if we are to bring ourselves into line with these conditions.

2. THE WORLD'S MINERAL ENERGY RESOURCES

Table I gives the estimated fossil fuel resources of the main areas of the world in units of 10^9 TCE (tons of coal equivalent). In the case of coal, the three rows represent -

1. The estimated reserves that can be obtained at not more than twice the present cost.
2. Total recoverable by human miners.
3. Total recoverable by telechiric mining.

Telechiric mining means developing the technology of telechirics to the point where a skilled miner in a control cabin on the surface can do any job down the mine (e.g. erecting machinery, operating it and repairing it when it breaks down) as skilfully as though he was down the mine. Fig.4 shows a model telechiric miner and Fig.5 is a diagram of the principle. When we have done this, we can develop the machinery for winning essentially all the coal laid down by nature in thin seams, heavily banded seams, seams as deep as we drill for oil and seams for under the sea. It will no longer be necessary to ventilate the mines with air, have men working in dangerous uncomfortable silica loaded conditions, or have men travelling daily long distances underground to the coal face.

Since most of the control and communications engineering necessary to produce mining telechirics has already been done in connection with carrying out engineering tasks inside nuclear reactors, it is probable that Britain could reach a position in which we could obtain most of the 500,000 M tons of coal at a rate of 200 M tons/year, by an expenditure of the order of £10M/year for ten years. In this way, no man would ever go underground and some 200,000 miners could be employed to produce the coal, doing the same skilled work as they do now by telechirs operated from comfortable safe control rooms on the surface. One control room would contain all the controls for the ten or so telechirs, which would be sufficient to run a mine, since each telechir can be manned by a miner on the surface in each of three shifts and this miner can hand over the controls to any other underground specialist when the task needs him.

The telechirs consist of arms, hands, binocular TV cameras and a light source fixed on a rotatable pair of 'shoulders' carried on a body suitable for either running about in the roadways (which need be no higher than the seam thickness, even when this is down to 0.3m (12 in)) or crawling past the props to do a job at the cutting face. An indicator board in the control room would tell all the ten men in the operating seats where in the mine all the ten telechirs were located, so that they can communicate directly by talking, the telechirs can work cooperatively, however far apart they are in the mine.

In the case of oil resources, the first row of figures represents the amounts extractable by present methods, at costs not more than twice the present cost; the second row represents the amount available if we can develop methods to extract 80-90% of the oil instead of only 25-40% as at present.

In the case of natural gas, the first row represents that recoverable by present methods at costs not more than twice the present cost, the second row includes all natural gas which could be obtained in regions from which it cannot be piped, e.g. the Middle East oil-fields where it is at present burnt to waste. Methods are already available for converting it into a mixture of methyl and higher alcoholics, and then it is as easily transportable as liquid petroleum. Research at Queen Mary College has shown that by adding 15% of this mixture to low octane petrol, one can attain a 95 octane rating without using any lead.

The table shows clearly how much more energy is available to man from coal than from oil and natural gas put together; from this one can conclude that oil and natural gas should be regarded as premium fuels and used only for the premium purposes for which they are ideally suited. Now liquid hydrocarbons are by far the most suitable fuel for air, sea and road

transport because they can be carried in light tanks, readily pumped into a lightweight (because high working pressure) engine and consumed with fourteen times their own weight of air which they pick up as they go along. Hence, we have the nonsensical situation in which people are burning up petroleum in stationery purposes for which coal is a perfectly good fuel and are doing research on how to produce oil from coal when the oil is all used up.

The other expendible fuel is the fissionable nucleus. The only naturally occurring nucleus which can be caused to undergo fission when bombarded by slow neutrons is U^{235} which is present to about 1 part in 140 in natural uranium. The energy available to man from the U^{235} in the concentrated ores is only of the order of 1/100 of that in the coal resources. However, if the breeder reactor can be developed as a reliable safe instrument, then we could eventually use up the main isotope in the U and also the Th which is available. Also, if we are prepared to spend the energy and crush the granite covering large areas of the earth, it is possible to extract 10-100 times as much natural U as is available in the rich ores.

The principal objections to nuclear fission as a solution to the long term energy needs of the whole of mankind are as follows.

1. The capital cost and energy for starting up power stations are such that it is very hard to envisage 7000 million people being served by them. Hence, it is likely to remain essentially a rich man's luxury.

2. It is essentially only available in large central power stations which are located well away from towns. Thus it cannot be combined with effective pass out steam heating systems; it requires a heavy concentration of capital expenditure and expensive distribution networks.

3. There is a grave risk of sabotage, theft, and terrorism at power stations and hijacking of Pu in transit from power stations to central handling plant - available in very few places in the world. Anyone with control of a power station can construct nuclear bombs.

4. Nuclear fission power stations will be derelict after 25-30 years and it will be impossibly expensive to dismantle them.

5. There is a real risk of accidental leakage of radioactive material to the atmosphere or to water from the power stations, processing plant or in transit.

6. We have not yet developed a method of looking after the highly radioactive waste from the reactor which does not require careful maintenance for hundreds of years by people who will get no benefit from it. A 1000 MW nuclear reactor produces 3 tons/year of such waste.

Nuclear fission is still only in the laboratory stage. It has not yet been achieved even in the laboratory as a continuous controlled self-sustaining reaction. It is therefore at least 30 years before it can be used on a large scale as a major contributor to man's energy needs and it is quite likely that we shall never be able to use it. It is now known that the only feasible fusion reaction is $T + D \rightarrow He + n + 17.6$ MeV. D(deuterium) is available in sea water, but T (tritium) has to be made by neutron bombardment of Li^6 which is present to the extent of 7.4% in natural Li. The world's deposits of natural Li are such that 67,500 tons of Li^6 could be won and thus theoretically we could obtain 215×10^2 J or 8.10^6 Mtce. This is about the same as the world's coal reserves in row 2 of Table 1.

The principle objections to fusion energy if it can be achieved are the same as 1 and 2 given above for nuclear fusion. The radioactive dangers do not occur significantly, but the power stations will be very expensive indeed and probably they will have to be at least 2000 MW.

3. RENEWABLE ENERGY RESOURCES

The only renewable energy resource which is used to make a major contribution to the world's energy needs at present is hydro power. Since 1 ton of water falling 1 km is equivalent to 2.70 kWh, whereas 1 kg of coal is equivalent to 7kWh, it is clear that one needs a large tonnage of water and a big head (viz 3:7 x 10^5 ton - km/hr, assuming 80% efficiency) to produce the same power as a thermal station burning 360 tons/hour of coal to produce 1000 MW. (40% efficiency assumed). Hence large hydro power generators are only practical where there is a large rainfall in high mountains, and it is possible to build reservoirs to give the power throughout the year. The capital cost is often twice that of a thermal station because of the necessary dams and other civil engineering works. However, the power is free and it can produce power for at least 50 years, the limiting factor probably in many cases being when the reservoir fills with silt.

It has been estimated that the total possible hydro power of the mountain ranges of the world is about 3 x 10^6 MW (3500 MTCE/ann.) which is roughly the present total industrial electricity production. About 8.5% of this is already being used, viz 210,000 MW (300 MTCE/ann.). The U S has 45,000 MW (50 MTCE/ann.) installed, which is 75% of its potential. This illustrates the fact that most of the unused hydro power is in mountain ranges far from industry - but nevertheless one can conclude that it is our duty to instal as much hydro power as possible in these places before the fossil fuels run out.

Tidal power suffers from the low head of a few metres available and the fact that even with two-way flow turbines, as in the Rance Estuary, one can only generate for about 1/3 of the 24 hours. The capital cost of the barrier carrying the turbines is high, but again, once installed, the energy source is free and forever. It has been estimated that if we used all the world's suitable tidal basins, we could generate 64,000 MW, i.e. 1/50 of the world's total hydro power. (If it produces power for 3000 hours in a year, this is equivalent to the total energy in 27 MTCE/ann.).

Wave power clearly suffers even more from the low head available and although in theory there is almost unlimited free power, in practice I am quite sure that the capital cost of installing and maintaining hundreds of miles of converters, far out at sea, makes this system quite impractical.

Geothermal energy has been used in Italy to produce 370 MW since 1904, because natural processes have produced a continuous supply of steam as water leaks into a volcanically hot region. California, New Zealand and Iceland are other places where such steam supplies are available, and it is estimated that 60,000 MW could be obtained for some 50 years by using all the available resources (total equivalent to the energy in 350 MTCE). The radial heat flow through the earths crust is only 0.06W/m^2, so that any attempt to generate steam artificially will require an enormous area for heat transfer.

Wind power is another traditional source of energy and will probably play an increased part in the future. In a 10 mph wind, which is of average strength the available energy is 200W/m^2, so that one would need to collect 25 m^2 with perfect efficiency to obtain 5kW. The problems with wind are the variable direction and velocity which make generation erratic and give dangerous forces in gales. The only large generator (1200 kW) which was built on a hill in the USA blew away, and I believe that millions of small generators of a few kW will be used locally for pumping water and power generation.

The sun was the source of all the fossil fuels over millions of years and when we have consumed them in a few hundreds of years, we shall be almost entirely dependent on sunshine again.

Just outside the atmosphere the solar intensity is 1.4 kW/m^2 peaking at about the visible

part of the spectrum and it is possible to collect more than ½ this figure on a clear day+ or, if one uses a non-directional flat plate collector, then in light cloud also. Low technology methods of using solar energy include :

1. Water and air heating in flat plate absorbers with glass covers (difficult to go above about 60 C because of heat losses).
2. Growing fuel crops such as wood, or materials that can be converted to methanol or hydrogenated to liquid hydrocarbons. Possibly the development of more sophisticated and more efficient biological photo synthetic processes.
3. Solar distillation of sea water to grow crops in desert areas.

High technology methods include :

1. Mirrors and lenses to concentrate energy to raise steam.
2. Selective coatings for flat plate absorbers to increase working temperature obtainable.
3. Photo voltaic cells for direct production of DC
4. Advanced chemical reduction processes by solar energy to produce fuels by reducing H_2O and CO_2.
5. Highly sophisticated big power stations, such as the 'power tower' with a large area of moving mirrors and the geosynchronous satellite which is in the sunshine 23 hours out of 24 and beams the energy down to a large collector in microwave form.

4. CONCLUSIONS

1. Man must come into full equilibrium with the environment by the time the fossil fuels are exhausted, which will be by 2,200 at the latest (unless mankind destroys himself first). Hence fossil fuels must be regarded as capital and by the time they are all spent we must have installed all the necessary equipment to provide man's continuing energy needs by the renewable supplies, particularly sunshine.

2. If we are to provide 7,000 million people with the good results of the industrial revolution and level off at that figure, then the energy consumption per capita in the rich countries must come down to around the present world average figure of 1.8 TCE and that in the poor countries must come up to this same figure.

3. We must do the research necessary to be able to win all the world's coal resources without men going underground.

4. We must immediately institute a policy of using the three premium fuels - oil, natural gas and electricity - for premium purposes only. It is criminally harmful to our grandchildren to use oil for purposes for which non-premium fuels can be used, especially coal, so that they have to make oil out of coal for their premium purposes.

5. We need to do much more research on the use of the renewable resources, particularly solar energy and wind energy, and also on storage methods for these renewable energies. We also need pilot schemes for the large area systems such as solar distillation for irrigation combined with growing a crop with a fuel and other value such as cotton, the waste of which can be hydrogenated to oil; the possibility of growing seaweed as a fuel must also be considered.

\+ Thus one could collect over the year an average of about 100 W/m^2 or on 1 km^2 100 MW x 8000 hours = 800,000 MWh/ann. equivalent to 110,000 TCE/ann.

6. We have to learn to regard fossil fuels as precious and thus devote very much more effort and capital to fuel saving, combined with pollution avoidance. This will have to be strongly encouraged by the Government, e.g. by putting a much more severe tariff on fuels, especially the premium fuels, or by subsidising the manufacture and installation of fuel saving equipment. The next four conclusions refer to specific examples of fuel saving possibilities in particular industries.

7. Transport Fuel Saving

We already know most of what is necessary to provide as much transport and travel as at present with greater convenience and safety, very much less pollution and noise and less than 1/3 of the present fuel consumption.

On a short term basis, we must develop a four-seater light car with a top speed of 50 mph doing well over 100 mpg - and we already know how to do this with a hybrid 10 hp diesel electric. A third year student in my department is building an experimental one. We must instal conversion equipment to make alcohol from all the natural gas wasted at present in the world and use it as motor fuel. We must develop public transport to be fully utilised and get all the long distance goods transport off the roads onto coal fired railways (direct or via electricity). We can develop low energy air bearings for trains to replace wheels on existing rails. We must develop air buses that use half as much fuel per passenger mile as present sub sonic planes; airships for intercontinental multi hundred ton loads and find new methods of ship propulsion that halve the present power consumption. We must revive the canals for low speed goods transport and develop self propelled dry lifting docks for carrying barges up hillsides in place of multiple locks.

In these ways we can get exactly as much travel and transport as at present with greater convenience, using less than half as much fuel. Further reduction will be obtained by developing quite new public transport systems (as described in my book 'Man, Machines and Tomorrow') and by a more economical lifestyle which people will accept when they see the advantages to their quality of life.

8. Industrial Fuel Economy

Basically, the essentials of a genuine fuel economy policy are :

1. Some type of subsidy which makes it immediately worthwhile for industry to instal fuel saving equipment, e.g. economisers, air heaters, better insulation, combustion control equipment. (This applies also to domestic fuel usage).
2. Making all consumer goods to last a lifetime and eliminating all built-in obsolescence.
3. No waste of fuels on unnecessary packaging and lighting displays.
4. Recycling all waste materials, especially non-porous metals and papers.

9. Total Energy Systems

No new thermal power stations should ever be built which do not use the waste heat for industrial or domestic purposes. Where it is essential to use electricity for low grade heating, it should be done by heat pumps.

10. Agriculture

No P and K should ever be allowed to drain to the sea and all valuable materials should be recovered from drainage water.

All compost and night soil must be recycled with complete conservation of N.

Drying should be developed on the vapour compression cycle, so that the latent heat of the water is not wasted. The leaf protein concentration process should be incorporated by using lucerne as a break crop on cereals.

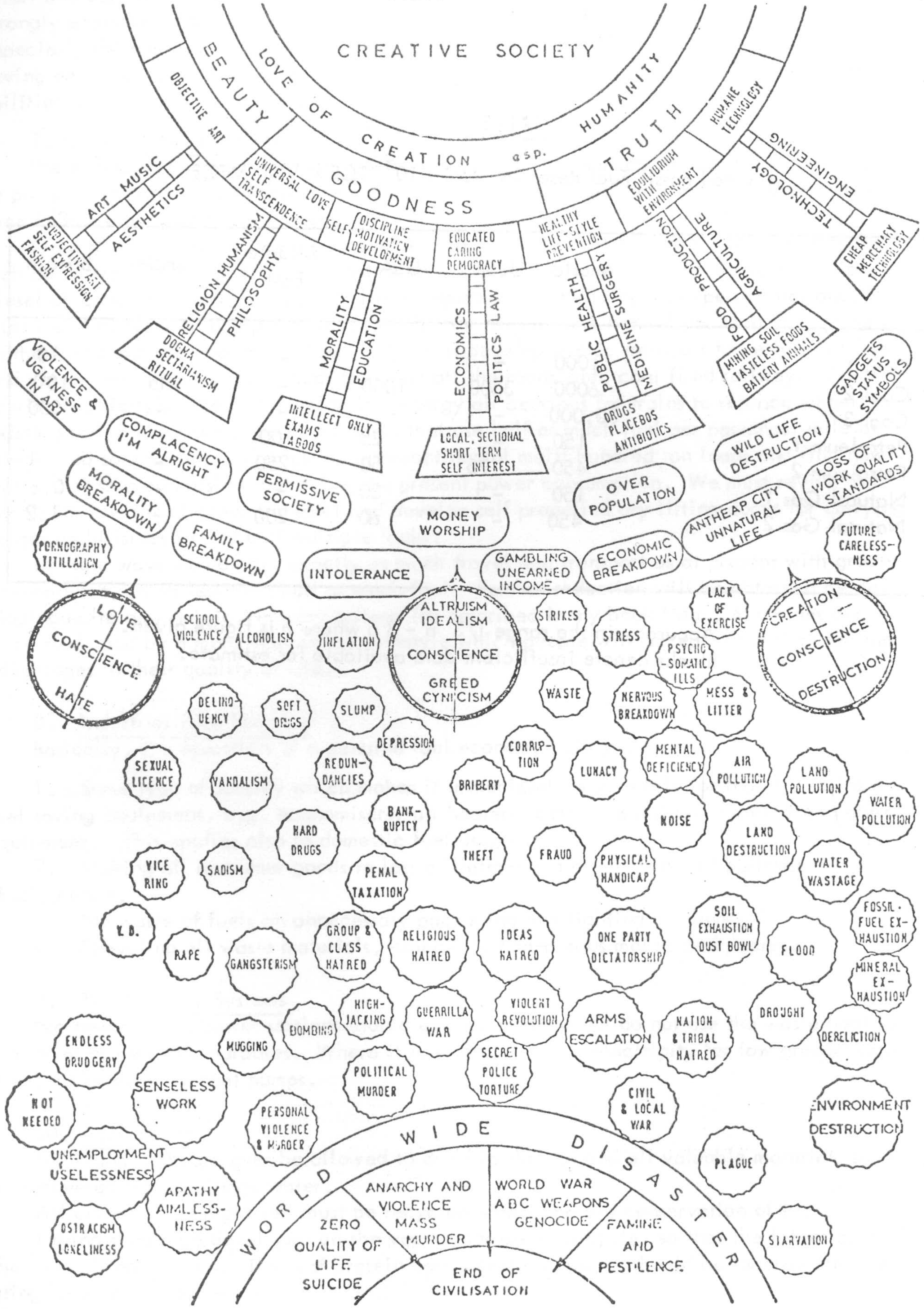
TABLE 1

Estimated Fossil Fuel Reserves Units 10^9 TCE = 1000 MTCE

	World	USSR	USA	Middle East	India	Britain
Coal 1	1000	-	-	-	-	10
Coal 2	6000	3500	1000	-	35	100
Coal 3	30,000	-	-	-	-	500
Petroleum 1	150	-	25	100	-	4
Petroleum 2	450	75	50	250	-	8
Natural Gas 1	150	-	30	-	-	0.6
Natural Gas 2	450	-	60	200	-	1.2

Accuracy in the range 1/3 n - 3 n where n is figure given.
Blanks denote insufficient data available for estimate.

FIG. 1



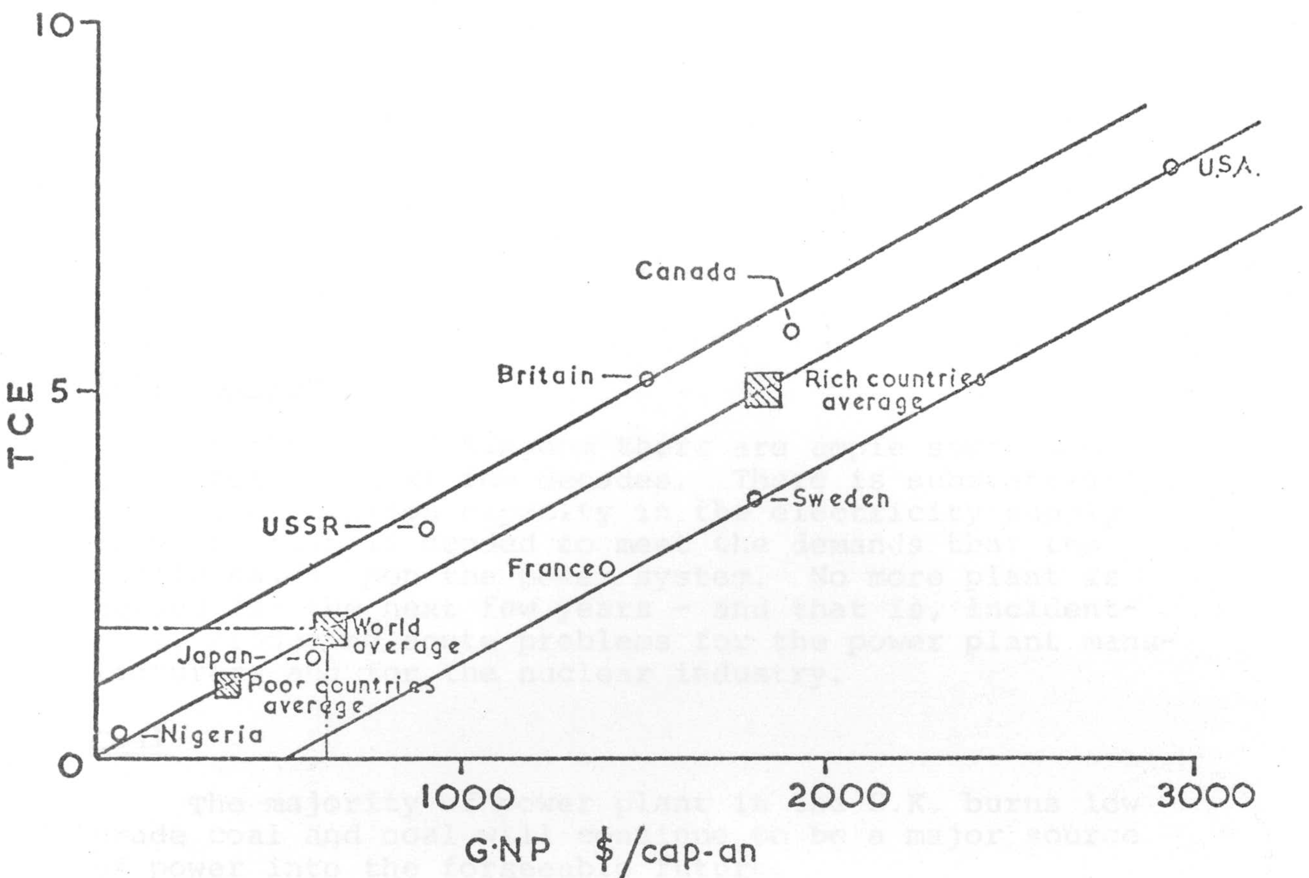


FIG. 2 Coal equivalent consumption per head as GNP for 1969

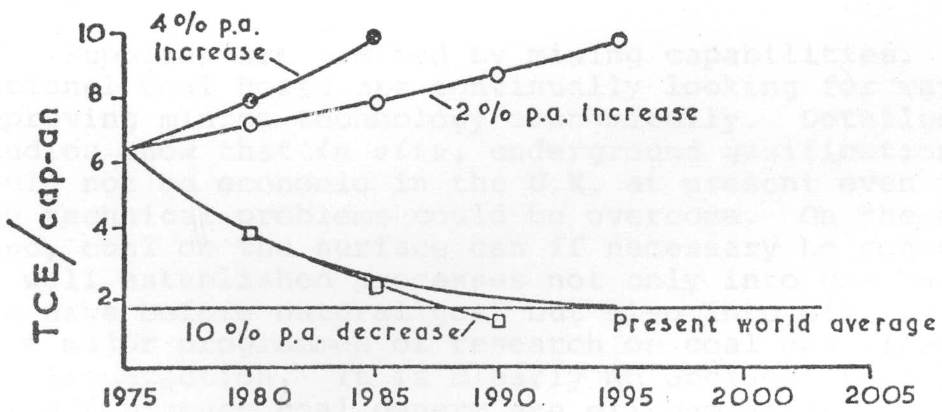


FIG. 3

Various possible futures for British energy consumption per capita

POWER RESOURCES FOR THE FUTURE

D. T. Swift-Hook

PRESENT SOURCES OF POWER

Introduction

In the United Kingdom there are ample sources of power for the next few decades. There is substantially more power station capacity in the electricity supply industry than is needed to meet the demands that the public makes upon the power system. No more plant is needed for the next few years - and that is, incidentally, producing acute problems for the power plant manufacturers and for the nuclear industry.

Coal

The majority of power plant in the U.K. burns low grade coal and coal will continue to be a major source of power into the forseeable future.

The United States, the U.S.S.R., China, South Africa, Indonesia - many countries around the world have plentiful reserves and we in the U.K. have our share. Our known, proven reserves of coal are 100,000 Mtonne, one thousand times our present annual consumption and nearly half of these reserves are technically recoverable, so there is enough coal for 300 years at present rates of consumption.

Supplies are limited by mining capabilities. The National Coal Board are continually looking for ways of improving mining technology economically. Detailed studies show that *in situ*, underground gasification would not be economic in the U.K. at present even if all the technical problems could be overcome. On the other hand, coal on the surface can if necessary be converted by well established processes not only into gas (as in the days before natural gas) but also into oil. The NCB have major programmes of research on coal gasification and liquefaction. It is clearly no accident that the world's biggest coal owners are oil companies.

Nuclear Power

There is some uncertainty on the nuclear needs of the country in the next few years but looking further ahead most of the scenarios which are at all probable call for the development of both coal and nuclear power.

This country has a well established nuclear capacity of magnox power stations meeting almost ten per cent of total electricity demand. Our next generation of Advanced Gas-cooled Reactors is just beginning to make major contributions which should amount to a further ten per cent in the next few years.

The country is well placed to move forward on the nuclear front when the need eventually arises.

Oil and Gas as Renewable Resources

There is no real immediate shortage of oil despite recent manipulations of the market by the Sheiks. This country is already producing much of its own oil from the North Sea and will be self-sufficient by 1980. Valuable as North Sea oil is, being relatively free from sulphur and containing a high proportion of light fractions, refining will still produce a black sludge for which a market must be found. This residual oil will be available for a power station fuel as long as North Sea oil lasts and some twenty per cent of our installed capacity of power generation is based upon residual fuel oil.

Oil from the North Sea will not be unlimited, but we should be self-sufficient until the turn of the century. After that oil may become a scarce commodity but it is actually replaceable. It is capable of being manufactured synthetically if need be when natural resources become too expensive. The South Africans already produce significant quantities of their oil from coal and if oil prices rise very much higher, other countries would find it economic to follow their lead.

This country has plentiful reserves of gas. The gas industry is growing rapidly in size and when supplies level out - as the presumably must in the next few years - they will be very high by the standards of past years. It is estimated that there is half as much gas under the North Sea as there is oil (and incidentally, there is probably even more coal). When gas runs out, substitute natural gas could be made from coal to extend the life of the gas system.

A great deal of interest has been shown recently in the Hydrogen Economy, i.e., the possibility of using nuclear power to manufacture large quantities of cheap hydrogen from water. Enthusiasts suggest that this could eventually replace natural gas and, by using such nuclearly produced hydrogen, reserves of coal, which are in any case sufficient for three hundred years, could be stretched by manufacturing oil.

In the longer term, fast breeder reactors and fusion both offer the possibility of virtually unlimited resources of energy.

ALTERNATIVE SOURCES OF POWER

Conservation and an energy insurance policy

Despite the existence of reasonably plentiful reserves of energy, there may well be problems in tapping them fast enough. It will clearly be prudent to adopt a policy of conservation and increased efficiency of utilisation.

Furthermore, our coming energy surplus must not be allowed to produce complacency. Recent history shows that shortages can arise from a variety of reasons. Plentiful oil in the ground is of little use if the Sheiks raise prices yet further. Coal becomes much less attractive when the miners refuse to dig it. The nuclear power industry has a magnificent safety record but what might be the effect of a single nuclear incident? The power industry has a good record in reducing pollution but suppose the anti-technology lobby achieves a position of greater dominance in years to come.

Alternative sources of power - solar, tidal, geothermal, wave and wind power - are being considered actively as an energy insurance policy. Even during a time of power plenty, diversification is very desirable.

In the longer-term energy, price rises seem inevitable. Mining will become more difficult as natural fossil and nuclear fuels are depleted and more complex processes become necessary. Then power sources with no fuel costs will look increasingly attractive.

Suggestions are often made that, by strong government policy, the energy consumption of the U.K. and the rest of the developed nations should be significantly reduced to help the underdeveloped countries of the world. The power supply industry is democratic in the sense that it tries to meet the demands of the general public. It lays plans to provide what it believes the public will require rather than dictating what they can have. It would require a major change in public attitudes and a more totalitarian approach by Government to enforce any other policy. Whatever attractions did arise, it seems more likely that it would press selfishly for economic growth rather than for sacrifice to benefit other countries. Consequently, whatever attractions a policy of reduced energy consumption might have, it was not considered as sufficiently likely to be included in the very broad spectrum of possible scenarios originally considered by the Department of Energy. The consequences of such a policy are not at all clear.

In any event, whatever the future may hold in the way of energy growth or energy shortage, our national research and development programmes should ensure that the appropriate energy technologies are available if and when they are needed. It will be prudent to include alternative energy sources - wind, wave, solar, tidal and geothermal - in our thinking.

Economic Considerations

It is characteristic of all the alternative sources of power which are being considered that, although the energy is apparently free, it is costly to harness. In conventional power station terms there are no "fuel" costs but the capital costs are high. None of the alternative methods is yet competitive with normal electrical power generation on a large scale, at current fuel prices.

This is not to say that special circumstances do not arise where small units are justified. In inaccessible places, where transmission costs would be prohibitive or where the load is too small to justify connection to the power system, a separate generator can be economic. A diesel set is usually found to be the cheapest and most reliable unit but occasionally windmills can be seen around the countryside.

By the same token, a system such as a tidal barrage which could not be justified purely on the basis of its power generation might become viable if it had economic benefits in other directions; land drainage, shipping, recreation and road construction could all be favourably involved. In the case of the Severn barrage, the C.E.G.B. have said that, assessed as a method of electricity generation, they see no prospect of its producing electricity more cheaply than other means or providing more than a limited contribution to the nation's power but they would be happy to join in any study mounted by the Government because of broader national considerations.

Apart from such special circumstances, it would be wrong to use alternative power sources on a widespread basis while they are more expensive than nuclear or fossil fuel systems. It would be equally wrong to ignore their potentialities for meeting possible future needs.

Variable Characteristics of Alternative Sources

Geothermal power is unique amongst the alternative energy sources in avoiding fluctuations in time but it is very variable geographically. Italy is fortunate in having large quantities of natural hot water around Larderello and generates several per cent of its electricity

(0.4 GW) geothermally. Other countries too have hot water or hot rocks with geothermal potential. The U.K. is not in such a favourable position but investigations are being supported by Government and EEC funds.

All the other natural sources are very variable and that limits their value appreciably. Reliability and continuity are considered to be of great importance for most electrical power systems. In former times, flour was not milled when the wind did not blow. But it would not be acceptable in a complex modern industrial society to have insufficient power when the sea was calm or the sun failed to shine. So, although these sources provide energy, they do not provide firm power. They would save on fuel costs but at the expense of additional capital costs beyond those needed to meet the peak power demand. It has already been pointed out that the additional capital costs are estimated to be fairly high. It might be possible to install cheaper peak load plant in conjunction with such fuel-saving schemes but the total cost would still be substantially increased.

STORAGE

Potential Benefits of Storage

If the alternative power sources could cover the periods when their energy is not available - every twelve hours or so in a tidal scheme, night-time and dark winter days for solar power, calm periods which may last for days on end for wind or waves - they would be considerably more attractive. As an example, with a typical windmill the cost of the storage battery installation is at least as much again as the windmill itself, if other back-up supplies are not available.

The potential benefits of storage are therefore very great and no discussion of alternative power sources would be complete without considering them. Unfortunately the cost of storing electricity is rather high and it is likely to be very expensive to store it for the periods of days which would be needed to complement solar, wind or wave power generation. Interestingly, nuclear power could eventually lead to a similar requirement for large-scale storage. Nuclear reactors have low fuel costs and when the stage is reached where nuclear power takes the base load (which is unlikely before the mid-1990s) there could be considerable advantage in storage to allow the nuclear plant to continue generating surplus energy at night to meet the peak demand the following day. This storage requirement for a few hours represents an easier economic target to achieve than the longer periods needed for natural energy sources.

Storage is, therefore, receiving attention in its own right, quite apart from its relevance to the somewhat variable power from natural sources.

Existing Methods of Storage

First of all, it should be recognised that a tank of oil, a truck-load of coal and a rod of uranium each represent cheap and compact means of storing energy. In a sense, therefore, any other method of storage is in competition with already established generation techniques. There is always one alternative to generating and then storing electricity at night for use the following day - and that is to store the fuel and wait until the following day to generate.

The only large storage systems today use pumped-water as at Ffestiniog. In Britain there is around 1GW pumped storage capacity and the Dinorwic scheme in Snowdonia will increase this to 2.5 GW in the early 1980s. These schemes, with their instant response to larger changes in power demand, can claim the extra economic benefit of providing all the "spinning reserve" that is required for smoothing out sudden changes in the supply system such as the break-down of a large generator. Future schemes will not then be able to claim similar benefit for two or three decades to come. Furthermore, there are very few suitable sites with potential for two lakes, one at the top of a mountain and one at the bottom. It would be possible to dig an underground cavern as the lower reservoir.

More expensive versions of tidal power schemes propose the use of two basins to incorporate an element of storage and to allow power generation when it is required, regardless of the phase of the tidal cycle.

Heat Storage

If it were practicable to dig large caverns, an alternative use to which they might be put would be to store compressed air. The air must be stored cool to avoid such problems as rock cracking. Thermodynamically, just as much energy must be removed in this cooling process as was put into the compression. It may, therefore, be advantageous to store this heat separately from the compressed air in, say, a regenerative pebble-bed heat exchanger.

A scheme equivalent to Dinorwic would require nearly a 40 m cube filled with more than 50,000 tons of, say, silica pebbles to store the heat and a compressed air store 700,000 cubic metres in volume. Such schemes are being studied by the C.E.G.B.

In this connection of heat storage it is worth noting that substantial capacity exists in the night storage heaters that are installed around the country on the extremities of the power-transmission and distributive network in the homes of many consumers. Electrical energy produced by the spare power station capacity that is available at night can be stored and released as heat the following day.

Large scale central storage of heat is being actively considered for its possible economic advantages in conjunction with both fossil-fuelled and nuclear plant. Either solar or geothermal heat could in principle be included in such schemes. Hot water is an obvious choice of storage medium in a steam cycle but other liquids could be preferable. Sodium would be compatible with a fast reactor but the economics do not look promising. Oils have high heat capacities and would need no pressure vessels although they would need heat exchangers; but on balance oil looks quite attractive for heat storage and such schemes are receiving detailed consideration on both sides of the Atlantic.

Other Methods of Storage

Battery storage of electricity is widely used in small units such as motor-cars. The cost is high compared with mains electricity and unfortunately there is no significant cost advantage in going to a larger scale as there often is with other power systems. Ordinary lead-acid batteries look more promising than nickel-iron, nickel-cadmium or hydrox fuel cells (which are used in space). New types of battery which run at high temperatures and are still at the laboratory stage of development but could eventually be two or three times cheaper than lead-acid include sodium-sulphur (which looks promising for electric cars), lithium-sulphur and lithium-chlorine.

Electrolytic hydrogen and oxygen could be stored and either used in a fuel cell or more widely for a range of energy requirements to produce what is known as the Hydrogen Economy. Various extreme forms are advocated but hydrogen is already used as a chemical feedstock and to produce lighter fraction oils by hydrogenation; further developments along those lines appear to be the most likely.

Many unconventional methods of storage have been suggested from time to time. A superconducting coil stores energy in the magnetic fieldthroughout its volume. Its cost is roughly proportional to the surface area and so the cost per unit of storage energy decreases with the size of the coil. A large enough coil should in principle be economic but the largest one yet built (e.g. for the 0.7m diameter bubble chamber at CERN) only stores a fraction of a megawatt-hour. A practical system would need to be at least ten thousand times bigger and is beyond the bounds of present technology.

Flywheels are commonly used for storing small amounts of energy for load smoothing. This is precisely the application of interest but the quantities of energy are, of course, very large. The energy stored per unit volume depends directly upon the allowable stress and the energy per unit mass varies inversely with the density of the fly-wheel. So, somewhat surprisingly, the greatest storage for a given load on the bearings is achieved not with heavy metal but with low density, high tensile strength materials such as glass fibre or better still, carbon fibre reinforced plastics. Unfortunately, costs are at present prohibitive.

Flywheels and superconducting storage can both be considered as "long shots".

CONCLUSION

Energy resources in this country seem adequate for the forseeable future over a wide range of credible scenarios, but it is prudent to assess the potential of alternative sources - wind, waves, solar, tidal and geothermal - in case difficulties or scarcities arise. Diversification provides an energy insurance policy.